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Original Scientific Paper

PROPERTIES OF STEEL-POLYPROPILENE HYBRID FIBERS REINFORCED CONCRETE

UDC 666.972.16

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Abstract. This paper present the results of mechanical properties of hybrid reinforced concrete made by adding polypropylene and steel fibers into concrete mixture. For the testing purposes were used steel fibers with hooked ends and monofilament polypropylene fibers. The total of 5 batches of concrete were made: concrete with addition of steel fibers, polypropylene fibers and their combination in amount of 0,5 % of the concrete volume. *The test results show that concretes made by adding of 0.4% steel and 0.1% polypropylene fibers have better performance compared to other concretes.*

Key words: *hybrid fibers, polypropylene fibers, steel fibers, concrete properties*

1. Introduction

In the recent years, a relatively new form building material: a hybrid reinforced concrete has been in the focus of attention. In general, the term “hybrid reinforced concrete” is used for materials whose cement matrix contains different types of micro reinforcement [1]. According to previous research, when concrete is loaded with the same external impact, hybrid reinforced concrete showed better cracking resistance than normal concrete [2]. By using the concept of hybridization, with two different fibers incorporated in a common cement matrix, the hybrid composite can offer more attractive engineering properties [3]. In general, addition of various combinations of fibers improve mechanical and dynamical properties of concrete [4]. Since now, different hybridization methods have been investigated in order to determine the influence of micro reinforcement shape, length, modulus and tensile strength of used fibers on concrete [5][6]. According to **Bentur** et al

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[7] improving mechanical and conductivity properties of concrete could be achieved by combining different types of polypropylene and steel fibers. The first type of fiber is more flexible and ductile, while the other is stronger and stiffer. So then, polypropylene fibers lead to improve toughness and strain capacity in the post-cracking zone, while steel fibers lead to improve first crack stress and ultimate strength. The influence of different fibers on the mechanical properties of high performance hybrid fibre concrete was investigated by **Qian et al.** [8]. Additions of a small fiber type had a significant influence on the compressive strength, but the splitting tensile strength was only slightly affected. In general, in the hardened loaded concrete, the polypropylene fibers with a small modulus of elasticity are inefficient for crack control, but then the inserted steel fibers with the high modulus of elasticity become prominent. Steel fibers act like micro-bridges in concrete, transferring stresses from one side of a crack onto the other. In this way reduce the concentration of stresses at the tops of cracks, which prevents their further development [9]. Presence of a considerable quantity of steel fibers in concrete reduces the workability of concrete which leads to the irregular consolidation of fresh concrete, which leads to the onset of micro-cavities and other deficiencies. By replacing the steel fibers with hybrid steel-propylene combination, the density of fresh concrete mix is reduced and its workability is increased while the polypropylene fibers partially negate the undesirable effects of steel fibers [10].

The main target of this research was to investigate benefits of using monofilament and steel fibers in the design on concrete mixtures. Mechanical characteristics of this way made hybrid reinforced concrete were compared to etalon concrete under the same test conditions.

2. Experimental procedure

2.1. Materials

In this study, Portland cement CEM I 52,5 R manufactured by CRH Popovac Serbia, was used for making concrete mixtures. Used cement fulfill all quality requirements recommended by SRPS EN 197-1 standard. The aggregate used in this research was a river aggregate originating from South Morava (Serbia). Three fractions of aggregate were used (0/4 mm, 4/8 mm and 8/16 mm) and all fractions fulfill the quality requirements prescribed by standards SRPS EN 206-1 and EN 12620. Particle size distribution of the individual fractions is presented in the Figure 1. Standard tap water was used for making all concrete mixtures and in order to reduce a water supply, as a reducer water additive SIKA Viscocrete 3070 was used.

In experimental research two types of fibers (polypropylene and steel) were used in order to product quality micro-reinforced concretes. Used polypropylene fibers belong to group of monofilament fibers producted by “Motvoz” Grosuplje (Slovenia). The type of this fibers was Fibrils S120 and belong to the group of circular cross sections and smooth surface fibers. The length of these fibers was 12 mm, while their average diameter was 0,037 mm. Used steel fibers belong to group of hook ended fibers produced by “Spajic” d.o.o. Company Negotin, Serbia. These steel fibers were made of steel marked C7D (number 1.0313) obtained by cold wire drawing. Type of used steel fibers was ZS/N 0.5×30 mm. The length of these steel fibers were 30 mm, while their average diameter was 0,50 mm. Used micro fibers were shown in the figure Figure 2.

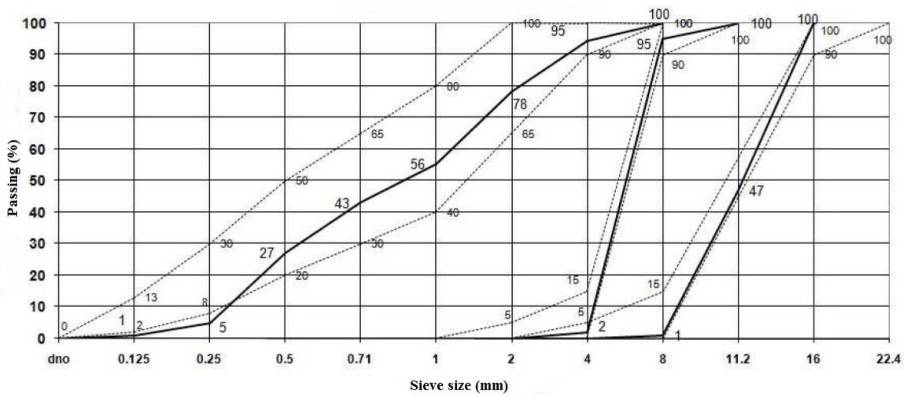

Fig. 1 Particle size distribution of used aggregate

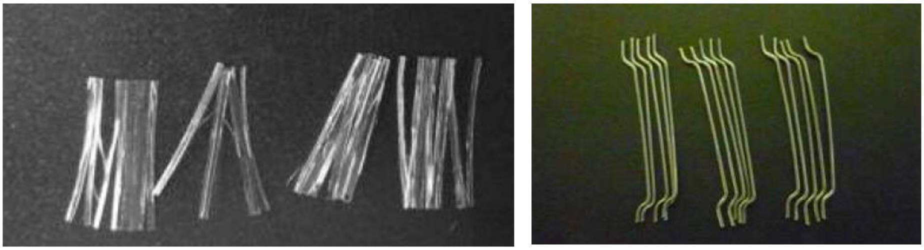

Fig. 2 Polypropylene (left) and steel (right) fibers used in experiment

2.2. Concrete mixture composition

For the purpose of determining the influence of different microfiber types and percentage on the performance of fresh and hardened concrete. Six batches of concrete were made. One batch of concrete was made only with steel hook addition in amount of 0,5 % of the volume. This batch is marked as “S5”. Other concrete batch was made with addition of polypropylene monofilament fibers in the amount of 0,5 % of the volume. This batch is marked as “P5”. The third batch of concrete was made by adding of 0,4% of steel and 0,1% of polypropylene fibers. According to using percentage of steel and polypropylene fibers in the concrete batch is names “S4P1”. According to the same analogy, other mixtures were named “S3P2” and “S2P3”. In order to compare the characteristics of micro reinforced concrete with ordinary cement concrete one more concrete batch was made. That batch was made without microfibers and it’s named as etalon “E”. Compositions of concrete mixtures for 1 m^3 of concrete are given in Table 3. The mixtures were made with the same water /cement ratio (m_w/ m_c = 0.45) and with the same aggregate /cement ratio (m_a/ m_c = 4.40). All mixtures were made with addition of the superplasticizer in the amount of 0,6% of the mass of cement.

Table 3 Composition of 1m^3 of concrete mixtures used in the experiment

Series of specimen	Aggregate			Cement	Water	Sika VSC 3070	Polyprop. fibers	Steel fibers
	0/4 mm	4/8 mm	8/16 mm					
	kg/m^3	kg/m^3	kg/m^3					
S5	782	435	522	396	178,2	2,38	-	39,25
P5	787	437	524	397	178,7	2,38	4,55	-
S4P1	783	435	522	395	177,8	2,37	0,91	31,40
S3P2	783	436	523	396	178,2	2,38	1,82	23,55
S2P3	784	436	523	396	178,2	2,38	2,73	15,70
E	792	440	528	400	180,0	2,40	-	-

2.3. Methods of examination

2.3.1. Methods of fresh concrete examination

Consistency of fresh concrete: In order to determine the consistency of fresh concrete, the method of setting by using Abrams cone was conducted. The testing was performed (Figure 3 - left) according to standard SRPS EN 12350-2:2010.

Fresh concrete density test: Testing of fresh concrete density (Figure 3 middle) was performed according to standard SRPS EN 12350-6:2010. This test was conducted by using a vessel of 8000 cm^3 volume, and concrete was vibrated.

Air content test: This test was performed in order to determine the percentage of air drawn into the fresh structure of concrete (Figure 3 - right). The test was conducted according to standard SRPS EN 12350-7:2010. In this case the porosimeter of vessel density was used.

Fig. 3 Testing the fresh concrete properties: Slump test (left), Density test (middle), Air content test (right)

2.3.2. Methods of hardened concrete examination

Bulk density of hardened concrete: Test of the density of concrete was performed by using the specimen cubes having side of 150 mm. The testing was performed according to standard SRPS EN 12390-7.

Compressive and flexural strength test: Determination of compressive strength was performed according to the SRPS EN 12390-3 standard. The samples of concrete cubes, having dimensions 150 x150 x 150 mm at the age of 2, 7 and 28 days. Testing was performed on a hydraulic press UTC-5740 manufacture by UTEST. Flexural strength of concrete prisms having dimension 100 x 100 x 400 mm was tested according to standard SRPS EN 12390-5 at the age of 28 days. The test was performed on the hydraulic press UTCM-6710 manufacture by UTEST.

Tensile splitting strength test: Determination of tensile splitting strength test was performed on cylindrical cores Ø150×300 mm according to standard SRPS EN 12390- 6 at the age of 28 dana. The test was performed on the hydraulic press UTC-5740 manufacture by UTEST.

Pull-off test: In order to determine adhesion of different materials to the concrete base the bond strength test was conducted. The test was performed according to SRPS EN 1542:2010 standard. Prismatic concrete samples having dimensions 200 x 200 x 50 mm were tested at the age of 28 days. According to standard, the preparation of samples was done by incision of Ø50 mm ring in the depth of 15 ± 5 mm. After cutting, steel seals of 50 mm and 20 mm high were gluing to the concrete surface by using epoxy glue, (Sikadur-31 CF Normal). Testing of the concrete samples was performed after two days by using „Pull-off“ apparatus manufactured by Matest (Dyna Z-16) of the capacity up to 16 kN.

Drop-weight test: Drop-weight test resistance was performed according to the recommendations of **Ukrainczyk** [11]. Concrete slab having dimensions 400 × 400 × 60 mm at the age of 28 days were fixed inside a steel frame and loaded by drop-weight of the 3kg mass from the height of 30 cm. The criterion for evaluation of the testing results is related to the number of weight impacts until the onset of the first crack (N1), as well as to the number of weight impacts until the failure of the slab (N2). For this purpose, the failure comprises either the complete propagation of a crack across the full height of the sample or a total failure (actual breaking) of the sample. The tests were performed on three specimens of each batch. Each specimen was tested to the maximum number of 40 impacts, unless the failure occurred prior to that. On the basis of the number of registered weight impacts was calculated the magnitude of energy expanded for the onset of the first cracks on the sample (E1), i.e. the total energy corresponding with the failure of the material (E2) according to the formula:

$$E_N = N \cdot E = N \cdot m \cdot g \cdot h \; [J] \tag{1}$$

where: E – energy consumed , corresponding to one weight impact,
E_N – total energy after N weight impacts,
m - weight mass – impact mass (m=3,0 kg),
g – Gravitational acceleration ($g=9{,}81 m/s^2$),
h – Initial height of the weight (h=0,30 m).

4. RESULTS AND DISCUSSION

4.1. Fresh concrete properties

The results of fresh concrete properties are presented in Table 4.

Table 4 Characteristic of fresh concrete properties

Series of specimen	Slump [mm]	Air content [%]	Density [kg/m^3]
E	110	3,0	2342
S5	100	3,6	2356
P5	30	4,8	2330
S4P1	90	3,7	2348
S3P2	75	3,9	2344
S2P3	55	4,2	2338

Consistency of concrete: On the basis of the test results, the highest slump was measured for the etalon mixture marked as “E” is 110 mm, while the concrete mixture “P5” had lowest slump value is 30 mm. Slump of concrete named “S5” was smaller than on etalon “E”. The difference between the slumps of this two measurement was 10 mm. The slump value of hybrid fiber reinforced mixtures is ranged in between the values of the mixtures “S5” and “P5”. As the number of polypropylene fibers, in a volume unit, is higher than the steel ones, it could be concluded that the compactness of concrete depends on the number, type and characteristics of used fibers.

Concrete density: The highest density was measured on the batch named “S5” and is 2356 kg/m^3. The smallest density was measured on the batch named “P5” and is 2330 kg/m^3. The density of hybrid fiber reinforced mixtures ranges between these two values. Also, as the value of the density of fresh concrete mix is influenced by the density of polypropylene (910 kg/m^3) and steel fibers (7850 kg/m^3) and it’s clear that density of concrete is in accordance of used fibers type.

Air content: According to the air content test results, the addition of polypropylene and steel fibers is in correlation with fresh concrete air content. By comparing the obtained results, it can be seen that the mixtures reinforced by the polypropylene fibers only have higher air content in comparison to the mixtures made with steel fibers only. This is logical regarding that the number of polypropylene fibers in a unit of volume is considerably higher in respect to the steel fibers. As expected, increase of polypropylene fibers in hybrid fiber reinforced mixtures increase the content of entrained air in fresh concrete.

4.2. Hardened concrete properties

The results of compressive strength, flexural strength, splitting tensile strength and bond strength by using “Pull-off” test properties are presented in Table 5, while the results of Drop-weight test are presented in Table 6.

Table 5 Characteristic of hardened concrete properties

Series of specimen	Density [kg/m^3]	Compressive strength [MPa]			Flexural strength [MPa]	Splitting tensile strength [MPa]	Bond strength by Pull-off [MPa]
		2 days	7 days	28 days			
E	2338	39,22	50,67	58,22	5,69	4,34	4,71
S5	2350	40,90	48,14	61,52	6,70	5,11	5,26
P5	2328	43,41	50,00	59,89	6,46	4,94	5,42
S4P1	2342	41,22	48,86	62,18	6,95	5,24	5,56
S3P2	2341	42,01	47,53	60,75	6,55	5,06	5,34
S2P3	2333	42,32	49,44	59,33	6,35	4,85	5,20

Compressive strength: Considering the types of concrete mixes which were analyzed in this research, the value of compressive strength and its increase in time was affected by the type and geometry of used fibers, as well as the ratio of steel and polypropylene fibers in the mixture. According to the results, the usage of fiber reinforced confirms the known fact that the addition of fibers, primarily the polypropylene ones, does not have a notable contribution in terms of increase of compressive strength of concrete. Namely, it is possible to considerably increase compressive strength of the concrete reinforced with steel fibers, but only in the case of a higher dosage of fibers (added steel fibers exceeding 0,5 % in volume). Since in this research, the steel fibers were added to the maximum amount of 39,25 kg/m3, i.e. 0,5 % of volume, it was logical to expect a small increase of compressive strength, in comparison with the reference concrete. In terms of concretes reinforced with polypropylene fibers, the increase of compressive strength is less prominent, which is explained mostly by the excess of entrained air during mixing and placement of concrete. By analyzing the results of compressive strength of 2 days old samples, it can be observed that there is a considerable contribution of fibers, primarily propylene ones, to the increase of strengths, which is logical because in that period of hardening the cement rock is the main factor of concrete strength. In the 7 days old samples, there is a decrease in compressive strength of fiber reinforced concretes in comparison with the reference concrete, while at the age of 28 days, fiber reinforced concretes have slightly higher compressive strengths in comparison with the reference concrete. At the age of 28 days, the highest value of compressive strength was recorded for the mixture marked as “S4P1” which is for 6,8 % more in comparison with the reference concrete. The increase of compressive strength of the mixture marked “S5” amounts to 5,7 %, of the mixture marked “S3P2” it amounts to 4,3%, of the mixture marked “P5” it amounts to 2,9 % and of the mixture marked “S2P3” it amounts to 1,9% in comparison with the reference concrete.

Tensile strength: The addition of fibers to the concrete primarily provide higher tensile strength of concrete. In a similar way as in case of the compressive strength, the flexural strength is influenced by type and geometry of applied fibers, as well as ratio of steel and polypropylene fibers in concrete. The mixture marked “S4P1” had the highest value of flexural strength which was for 22,1 % higher than the reference concrete. The increase of the flexural strength of the mixture marked “S5” was 17,8%, of the mixture “S3P2” it was 15,1 %, of the mixture “P5” it was 13,5% and of the mixture “S2P3” it was 11,6 % in comparison with the reference concrete.

Splitting tensile strength: According to the test results of the splitting tensile strength it can be concluded that fiber reinforcing, regardless of the type of fiber, contributed to improvement of this mechanical characteristic of concrete. The highest value of splitting tensile strength was achieved by the mixture marked “S4P1” which is for 20,7 % higher than the reference concrete. The increase of splitting tensile strength of the mixture marked “S5” is 17,7 %, of the mixture marked “S3P2” it is 16,6 %, of the mixture marked “P5” it is 13,8 % and of the mixture marked “S2P3” 11,8 % in comparison with the reference concrete.

„Pull-off“ test: The highest value of bond strength by „Pull-off“ test was achieved by the mixture marked “S4P1” which is for 18,0 % higher in respect to the reference concrete. The increase of bond strength of the mixture marked “S5” is 15,1 %, of the mixture marked “S3P2” it is 13,4 %, the mixture marked “P5” it is 11,7 % and the mixture marked “S2P3” it is 10,4 % in comparison with the reference concrete. It should be emphasized that the value of bond strength by „Pull-off“ test was to great extent affected by the arrangement of reinforced fibers within the concrete composite. Namely, since the polypropylene fibers are smaller and more numerous in comparison with the steel ones, the distribution of these fibers within the concrete composite is more homogenous in terms of quantity and direction. It is particularly important for the surface parts of the concrete sample (in practice, it is a structural concrete element) on which the value of bond strength by „Pull-off“ test is tested. It is logical that higher bond strengths by „Pull-off“ tests will be obtained, if a larger number of fibers in the surface zone of concrete are oriented in the direction or at a small angle to the direction of pull-off force action.

Table 6 Drop-weight test results

Series of specimen	The energy consumed for the onset of the first crack [J]	The energy consumed for the failure [J]
E	61,8	88,3
S5	132,4	> 353,20 (927,0)
P5	88,3	238,4
S4P1	158,9	> 353,20 (697,5)
S3P2	132,4	> 353,20 (547,4)
S2P3	105,9	> 353,20 (441,5)

Drop-weight test: Steel and propylene fibers contributed to the increase of the impact resistance of concrete, both in terms of an increase of the absorbed energy until the onset of initial damage (first cracks) and in terms of retaining serviceability during a protracted exposure to impact loads after the onset of the first cracks. Micro-reinforcing using only steel fibers, as well as hybrid micro-reinforcing contributed more to the enhancement of the impact resistance of concrete than the micro-reinforcing using only polypropylene fibers. The hybrid micro-reinforcing where a combination of steel and polypropylene fibers in the 4:1 ratio was implemented, caused the highest demand of the energy required to cause the onset of the first cracks, in comparison to other concretes. However, the highest demand of energy required for the impact load failure of a slab was used for concrete which was micro-reinforced with steel fibers only.

5. Conclusion

In the present paper, a study of the effect of different fibers on physical-mechanical properties of hybrid reinforced concrete was carried out. Concrete mixtures were designed by using Portland cement and polypropylene and steel microfibers in the amount of up to 0,5 % of the volume in order to improve hybrid concrete properties.

The results can be summarized as follows:

- The workability of the fresh fibers in concrete mixtures depends upon the proportions of the micro-fibers. Also, increase of polypropylene fibers in hybrid fiber reinforced mixtures increase the content of entrained air in fresh concrete, but also reduce slump and fresh concrete density.
- The hybrid micro-reinforcement contributed to enhancement of mechanical characteristics of concrete in comparison to the reference concrete.
- Micro-reinforced concretes are more resistant to impact load in comparison to the non-reinforced concretes, irrespective of the type of added fibers.
- The hybrid micro-reinforcing where a combination of steel and polypropylene fibers in the 4:1 ratio was implemented, caused the highest demand of the energy required to cause the onset of the first cracks, in comparison to other concretes. However, the highest demand of energy required for the impact load failure of a slab was used for concrete which was micro-reinforced with steel fibers only.

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MIKROARMIRANI HIBRIDNI BETONI ARMIRANIH ČELIČNIM I POLIPROPILENSKIM VLAKNIMA

U ovom radu predstavljeni su rezultati ispitivanja mehnaičkih karakterisitka hibridnih betona armiranih mikrovlaknima vlaknima. Ispitivanje je sprovedeno na mešavinama betona spravljenim sa čeličnim vlaknima zakrivljenih krajeva i monofilamentnim polipropilenskim vlaknima. U svrhu ispitivanja napravljeno je ukupno pet betonskih serija Jedna betonska serija spravljena je samo sa čeličnim vlaknima kao dodatkom, *dok su preostale četiri serije betona spravljene sa kombinacijom čeličnih i polipropilenskim vlaknima u iznosu od 0,5 % zapremine. Prema rezultatima ispitivanja može se zaključiti da betoni spravljeni sa dodatkom 0,4% čeličnih i 0,1% polipropilenskih vlakana imaju bolje mehaničke karakteristike u odnosu na ostale mikroarmirane betona spravljene pri drugim procentualno-zapremninskim odnosima mikrovlakana.*

Ključne reči: *hibridna vlakna, polipropilenska vlakna, čelična vlakna, karakteristike betona*

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CHARACTERISTICS OF MULTIFAMILY HOUSING DEVELOPMENT IN THE POST-SOCIALIST PERIOD: CASE STUDY, THE CITY OF NIŠ

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Abstract. *The paper deals with characteristics of multifamily housing development (MHD) in specific conditions of post-socialist transition. Multi-layered political, institutional and socio-economic changes have influenced the change in the urban structure of cities, including housing areas. Time distance of thirty years from the beginning of transition in Serbia, gives us a good position to monitor and fully understand the effects of changes, including the last and longest-term phase of transitional process – urban changes. The development of multifamily housing is examined on the example of the city of Nis, a typical socialist industrial city that underwent dramatic changes in the post-socialist period and represent a good testing ground for transitional changes and their effects. The goal of the paper is to recognize different types of multifamily housing and the transitional changes that led to certain type of development and their spatial distribution in the city. The research suggests that multifamily housing development is especially influenced by privatization in the initial phase of transition, restitution in the later phase of transition, changing role of public and private sector in housing development, as well as changes in urban planning.*

Key words: *multifamily housing, urban changes, post-socialism, transition, City of Niš*

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1. INTRODUCTION

Period between 1989 and 1992 was marked with fall of communist regimes throughout the Central East and South East European countries (CEE and SEE), accompanied with a deep political and economic crisis, and in some countries, ethnic wars and disintegration of states. The end of state socialism marks the beginning of reforms leading to market economies and democratic governance, hence the term "transition" is commonly used for the post-socialist period [1][2]. Transition in former SFR Yugoslavia took place under specific political and socio-economic circumstances, with a delay of a decade compared to other countries in the region. It can be said that Serbia is still going through the transition process, i.e. is in the phase of "mature transition" [3][4]. Post-socialist transformations can be described by a series of transitions: the first - institutional transformations, the second - social transformations and the third - urban transformations [5]. The transition begins with political decision-making, which is the fastest, short-term change, while other changes are slower and last longer. The change of urban structure is the third and longest-lasting phase of transition, the effects of which can be seen only after a certain period of time. The transformation of the built environment is the result of functional changes in cities, the most significant of which are the expansion of commercial areas, the transformation of industrial zones and the changed character of housing [6].

Despite significant differences in public policies and institutions in the CEE countries, housing models in the socialist period share numerous similarities that make the so-called "Eastern European housing model" [7]. The Eastern European housing model had a large number of sub-models and variations, but two major common characteristics of all sub-models stand out: 1) state domination in housing construction and distribution with limited and subordinate market functioning; 2) housing as a social right, intended to meet housing needs, and not as a commodity [8]. However, the peculiarities of the Yugoslav self-management socialist system, such as greater importance of market-like relations in the mainstream economy with more liberalised income regime and consumption patterns [9] led to several divergences in comparison with the 'pure' East European housing model and its sub models. The first important divergence is the different state role in housing, in the sense of early decentralization and transfer of state responsibility in housing provision, while the second is the decisive role of socially owned enterprises as housing developers from the early 1950s. However, the development of the housing sector during the socialist period was determined by two important drivers: 1) housing was a political priority and 2) centralized management of the economy enabled governments to direct resources to certain sectors [10]. The consequences of transition in the housing sector can be shortly described as the disintegration of the Eastern European housing model [11][12]. By moving away from this housing model, market mechanisms gain a more significant role in the housing sphere, while state responsibility, power, and resources weaken. State budgets for investment in housing and subsidies are reduced, with a simultaneous reduction of state housing funds due to privatization and / or restitution [8]. As stated by Stanilov (2007), the main principles of housing reform are: privatization, deregulation, and reduction, i.e. cessation of state funding [13]. Rapid withdrawal of state participation in the housing sector, through a drastic reduction in state subsidies and a reduction in the direct supply of housing, resulted in an escalation of the housing crisis, which was noticeable even in the period of socialism. The intensity of housing construction was reduced at the end of the 1980s, before experiencing a sharp decline in all CEE countries in the early 1990s [14] and reached a minimum in 1993-94 [13][15].

Recovery of the housing sector began in the mid-1990s, first in the countries that started political and economic reforms earlier (Czech Republic, Hungary), and later it was transferred to other countries. The recovery process was very slow, so in the year 2000 none of the CEE countries reached the level of housing production from 1990. On the average, new housing construction in the CEE countries declined from 4.4 dwelling units per 1,000 residents in 1990, to 1.8 units in 2000. In comparison, during the same period, housing production in Western European countries showed a slight decrease from 6.5 to 5.8 units, while in the United States the rate of new housing construction increased from 5.2 to 5.5 units [13]. Simultaneously with the state withdrawal from housing construction, started the privatization of the existing housing stock and housing development with private capital. The conversion of the state property into private was carried out through mechanisms of restitution (reprivatization) and sale of state /socially owned apartments to the sitting tenants [2][13]. Apartments were sold to tenants at prices significantly lower than the market ones - through so-called “gifted privatization” or low-price model of privatization [12][16] in order to mitigate the negative social effects of the transition [8][17]. The degree of application of these mechanisms varied from one CEE country to another. In the Balkans and Lithuania and Hungary, the housing privatization process was largely completed by the mid-1990s, using socialist “top-down” approach in reform leading to the sale of most socially owned housing units [14], while in other countries (Czech Republic, Slovakia, Poland, East Germany) privatization was slower and restitution was more prevalent.

In Serbia, the privatization of social housing began in 1990 with the adoption of the *Law on Housing Relations* ("Official Gazette of the RS", No. 12/90, 47/90, 55/90 and "Official Gazette of the RS", No. 3/90 and 7/90), while the restitution process began much later, in 2011, with the adoption of *the Law on Restitution of Confiscated Property and Compensatio*n ("Official Gazette of RS", No. 72/2011, 108/2013, 142/2014 and 88/2015 - US decision) and establishment of Directorate for Restitution. First requests for restitution were submitted in 2012, and the deadline for submitting requests for restitution was 2014. Housing privatization and restitution, combined with the strengthening of private capital, have greatly influenced the development of multifamily housing. In Serbia, where the privatization of the housing stock was carried out first, the upgrades of existing multi-story buildings appeared as dominant form of housing construction for the market in the early transition, especially in second-tier cities [18]. New construction on greenfield locations first developed on the outskirts of the city, and only at a later stage, along with land restitution and strengthening of private capital, multifamily housing construction spread to central city zones.

This paper deals with characteristics of housing in the period after the 1990s, with research focus on multifamily housing (MH). Accordingly, the key research aims are:

- to investigate the specific economic, political and social changes until the 1990s that set a platform for the emergence and evolution of multifamily housing (re)development modes, focusing on links between the housing system and its characteristics, housing institutional arrangements and regulatory framework.
- to scrutinize the impact of development changes on the chosen MHD mode - new construction on greenfield locations on the outskirts of the city, assessing the extent of its physical and socio-economic effects on the quality of everyday life at the neighborhood level.

The research is conducted in the city of Niš - former industrial and macro-regional center which undergone significant urban changes in post-socialist period, including those in housing sector.

2. Multifamily Housing Development in the City of Nis after the 1990s

The city of Nis was one of the most important industrial centers in Serbia in the socialist period. The development of the industry was accompanied with increase in the number of inhabitants and increased needs for housing. In the period from 1961 to 1981, the housing stock of Nis developed intensively, following the dynamics of population growth. From 1981 to 1991, the increase in the number of housing units was even more visible, given the gradual slowdown in population growth. Statistics show that since the 1980s Niš had an average of 1.1 apartment per household. This is mainly due to a higher share of flats in private family houses with a very low occupancy rate, while multi-story housing areas experienced continuous overcrowding and low space consumption. In general, 19.6 % of the population lived in overcrowded apartments, three or more persons per room, while 23.6 % was on the borderline of falling into this category [19][20]. Under the influence of the economic downturn and reduced budget allocations for housing development (approximately 0.1% of the city budget from 2000 to 2005), the housing sector in Nis has experienced regressive changes since the first phases of post-socialist period [19]. In 1991, about 1,450 housing units were built (approx. 5 apartments per 1,000 residents), and in 2003 that number was reduced to 450 housing units (approx. 1.8 apartments per 1,000 residents). In line with the trend of privatization of social housing in Serbia, the housing stock in Niš was almost completely privatized during the 1990s (98.4%) [21]. In 2002, only 385 socially owned housing units were unpurchased, which is a negligible percentage of the total housing stock [20].

The main characteristics of housing development in Niš during the 1990s and the beginning of the 2000s include the following [22]:

- lack of significant public investments in housing construction and complete absence of investments in construction of apartments for rent;
- lack of subsidies for individual housing construction, as well as insufficient number of locations for this type of construction;
- emergence of a larger number of “small” private investors, trying to build with money from pre-sold apartments or with money acquired through other business activities;
- lack of available construction sites in the center and insufficient interest of investors for the construction of MH in suburban settlements, long and complicated procedures for resolving property-legal relations and unsatisfactory situation in the cadastral system;
- construction of apartments on the flat roofs of existing buildings (multi-story housing extensions - MHE) of varying, but mostly poor quality;
- design and construction of small (often substandard) housing units;
- business difficulties of “traditional” builders - public construction enterprises and the emergence of small and medium-sized construction companies, only partially qualified for larger construction tasks.

The following period is characterized by the complete disappearance of large socially owned enterprises from housing construction, due to their privatization and collapse. “Građevinar”, the leading construction company in Niš in socialist period, was unsuccessfully privatized in 2007, sharing the fate of many other socially owned companies. Private sector, comprised of former socially owned enterprises and new medium - small construction enterprises, strengthens over time and takes the leading role in housing construction. The gradual economic recovery and strengthening of financial institutions made possible the introduction of mortgage financing. Housing construction was encouraged by establishment of the National Corporation for Housing Loans Insurance (established in 2004) which covers up to 75 percent of losses incurred by financial institutions and the reduction of VAT rate on new apartments from 18 to 8 percent [13].

The state intervention had positive effects on housing construction, which has been increasing since 2005. The withdrawal of public sector and strengthening the private sector marked housing development in later phase of transition and affected the type, scale and spatial distribution of MHD.

2.1. Public and private sector in multifamily housing development

Having in mind the changing role of public and private sector, multifamily housing can be classified according to the source of financing as follows: 1) construction in public sector; 2) construction in private sector; and 3) public-private partnership . In addition to direct impact of the capital, the change of public-private relations in ownership of housing and construction land through privatization and restitution affected the development of certain types of housing, as well as their spatial distribution.

The participation of the public sector in multi-story housing construction occurs in three forms: 1) remnants of the socialist system in form of solidarity funds in companies, i.e. investment in apartments for workers; 2) apartments for armed forces (army, police) and university staff; and 3) social housing.

From the early 1950s, in the Yugoslav housing sub-model provision of housing was transferred from the state level to socially owned enterprises [23]. Solidarity funds continued to exist in the period of transition and companies still were obliged to allocate part of the monthly income for housing. In addition, companies in all sectors of ownership could finance housing for their employees, with no legal obligation to define transparent criteria for distribution of apartments, even for the state-owned companies [9]. As the ownership of enterprises changes from public to private, the source of financing changes too, so it can be only partially considered a construction in public sector. This type of construction is represented in a small share and it is related to successfully privatized enterprises, such as Tobacco Factory.

Another form of construction in public sector is housing for members of armed forces, funded from the national budget. This type of housing development makes a small share in overall housing construction and it is being funded from the national budget, so it is not of great importance for this study. The exception is the project “Novi Niš”, which is significant from the aspect of land-use planning and public-private partnership in housing construction. Large portions of land in inner city area of Niš are occupied with former military complexes. These locations are very attractive for development of new city sub-centers, so the Ministry of Defense, as a land user, concedes the land to the City, in exchange for apartments for the army members. In order to fulfill the commitments, the city of Niš enters into a public-private partnership.

The third and most important form of construction in the public sector is social housing. After the mass privatization of apartments in the early 90's, socially owned housing stock almost completely disappeared, but the privatization did not provide the expected funds for meeting the housing needs of lower income population [24]. Namely, during socialism and until the early 2000s, social housing was financed from solidarity housing funds (SHF) in accordance with legal obligations. After 2004, the SHF have gradually extinguished or have been transformed into new city housing agencies, first basic institutions of the future social housing system in Serbia. The main problems of social housing construction were: 1) lack of public finances and 2) lack of municipal-owned construction land, due to the nationalization of property of local government by the *Law on Funds Owned by the Republic of Serbia, 1995* ("Official Gazette of the RS", No. 53/95). As a result, local governments could not acquire the land on the market and create "land banks" for housing construction for non-profit sale or lease [24]. Social housing development in Niš started in 2004, after the City Housing Agency was formed, but it is still on a very low level. Dealing with extremely negative economic trends, the city municipality did not succeed in establishing the promised housing strategy until as late as 2007 [25].

Unlike the socialist period, when multi-family housing construction was almost entirely in hands of public sector, in the post-socialist period the private sector becomes dominant, while the participation of public sector is almost negligible. Namely, apart from the before mentioned examples of construction in public sector and public-private partnership, the rest of construction is exclusively in the private sector.

In the following, the paper deals with various modes of multi-family housing appearing and shaped by private developers, their characteristics and spatial distribution, with emphasis on new construction on greenfield locations on the outskirts of the city.

2.2. Types of multifamily housing in the post-socialist period

The scale of housing construction and its spatial distribution can be briefly explained through the interrelation of available construction land (land ownership) and private capital. In the initial period of transition, private sector was weak and still undeveloped, while the construction land in the inner city area was unavailable due to unresolved property rights, which resulted in construction "without building parcel" - multistory housing extensions in inner city area, and new construction on greenfield locations on the outskirts of the city. The next phase is characterized by strengthening of private sector, greater availability of construction land in the central city zone, spread of construction to the city center and increased scale of construction. In line with this, the following types of post-socialist multi-family housing can be noticed in urban fabric of the city of Niš:

1) multi-story housing extensions of existing residential buildings (Fig. 1);
2) new construction on greenfield sites on the outskirts of the city (Fig. 2) ;
3) infill development (Fig. 3);
4) reconstruction of the city core (Fig. 4);
5) construction of larger scale on brownfield sites (Fig. 5).

Fig. 1 Type of multi-family housing: Multi-story housing extensions of existing residential buildings. A - pre-socialist period (1950s); B, C - socialist period (1980s) (source: authors)

Fig. 2 Type of multi-family housing: Multifamily housing on greenfield locations on the outskirts of the city – the layout of housing area Somborska-Studenička. A - 2006 (source: https://gis.ni.rs, accessed 2019); B - 2021 (source: https://a3.geosrbija.rs/)

Fig. 3 Type of multi-family housing: New infill development - LHE Bulevar Nemanjića (source: authors)

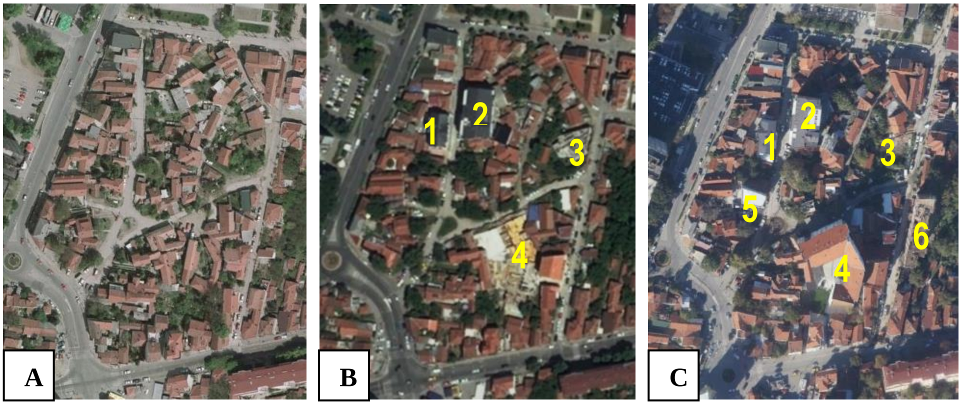

Fig. 4 Type of multi-family housing: Reconstruction of the city core period 2006-2021. A - 2006 (source:https://gis.ni.rs, accesed 2019.); B - 2011-2013 (source: www.geosrbija.rs/); C - 2021 (source:https://gis.ni.rs)

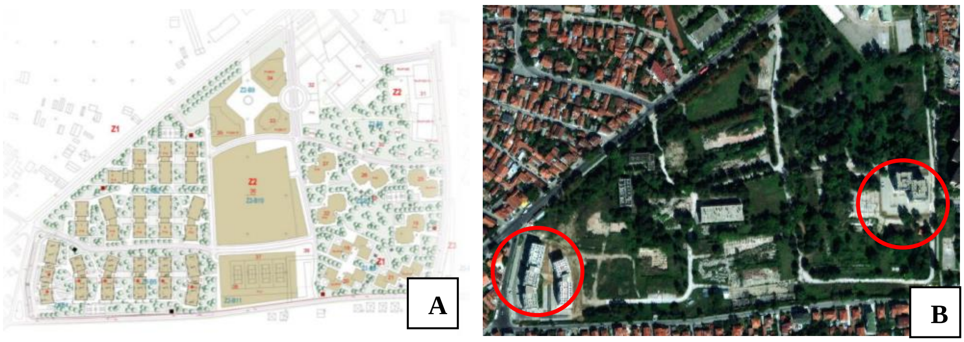

Fig. 5 Type of multi-family housing: Construction of larger scale on brownfield sites - Novi Niš. A - project of a residential area (source: https://novinis.com/), B - aerial view of location with marked new construction (source: https://a3.geosrbija.rs/)

The following section deals with multifamily housing on greenfield sites on the outskirts of the city as one of dominant post-socialist housing development types. Although similar to socialist large housing estates, it originated under modified conditions in post-socialist period, which resulted in specific physical-functional features. Shaped by private capital from the very beginning, accompanied with poor planning and weak institutional control, it represents a typical example of what is better known as “investor urbanism” [26].

3. MULTIFAMILY HOUSING ON GREENFIELD SITES ON THE OUTSKIRTS OF THE CITY – SOMBORSKA-STUDENIČKA

The multi-story housing development in Niš was in full swing in 1970s, which caused the need for considering directions of further development, i.e. analyzing new locations for housing development and their economic viability. For the purpose of further development, the Study of Long-Term Development of Collective Housing in Nis 1981-1991-2000 was prepared in 1981 [27]. The Study analyzed three possible variants - two of which were greenfield sites and the third one a reconstruction of the city core. Cost analysis showed that the reconstruction of the city core is about 30% more expensive than construction on greenfield locations, due to the high costs of displacement of residents. Therefore, recommendations were given for the construction on greenfield locations, while the reconstruction of the city core was seen as a continuous activity throughout the whole period 1981-2000 [27]. The proposed locations were built into the General Urban Plan of Nis 1995-2010 (“Official Gazette of the City of Nis”, No. 13/95), thus providing a planning framework for future MH construction on greenfield locations on the outskirts of the city. Housing area along Somborska and Studenička streets (see Fig. 2) is one of two greenfield locations proposed for further development by the Study and the General Urban Plan.

3.1. Development conditions

Development of the Somborska-Studenička multifamily housing area began in the early 2000s on the very outskirts of the city, next to the family housing area. In the last fifteen years, the area has experienced rapid development with the strengthening of private capital. Unlike socialist housing estates, built on state owned land with no market value, this area has developed on fragmented plots of agricultural land acquired by investors from private owners. Since the housing was exclusively intended for the market, private investors strived for maximum utilization of construction plots, often disregarding the rules of construction set in planning documents. Weak institutional control over the implementation of planning documents has led to multiple deviations in construction such as exceeded maximum number of floors, occupancy index, floor area ratio, insufficient distances between buildings, etc.

Although the area was covered with General Urban Plan 1995, detailed zoning plans followed only later, after it was already affected by illegal construction. As Vasilevska et al. (2014) pointed out, the area is unique because development began before planning [28]. The first Detailed Zoning Plan (DZP) for this area, DZP “Somborska-centar” (“Official Gazette of the City of Nis” no. 106/04), was adopted in 2004 and the existing illegal housing was incorporated in the plan which partially affected the shape of building blocks. According to the DZP, the whole area was intended for housing and was divided in the following zones: “A” - neighborhood center with housing (max. allowed number of floors: GF+4); “B” - family or multifamily housing (max. allowed number of floors: GF+3) and “V” - multifamily housing and commercial use (max. allowed number of floors: GF+4) (see Fig. 6). The largest part of planning area was intended for low-rise housing (GF+3). Maximum allowed number of floors, as well as other planning parameters defined within the DZP, were already exceeded before the plan came into force, which led to “re-planning” of the area and adoption of new DZPs.

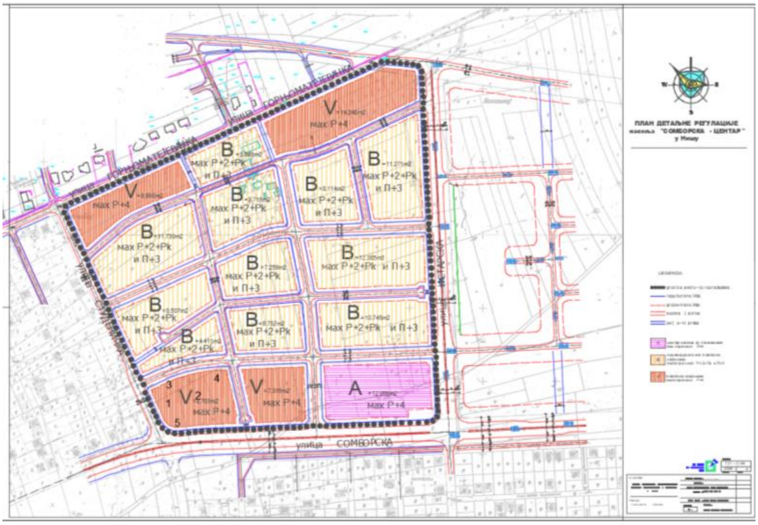

Fig. 6 Detailed Zoning Plan “Somborska-centar” (“Official Gazette of the City of Nis” no. 106/04).

New planning documents, i.e. modifications of existing planning documents, were adopted with aim to establish control over the development of the area, but they only legalized the existing deviations and created a basis for further deviations. Namely, subsequent planning documents increased the allowed parameters to enable the legalization of existing buildings, but later construction often exceeded even the newly set parameters. As Kiss (2007) pointed out, in the spirit of the neo-liberal thinking, which quickly took over the post-socialist states, the decisive factors in urban development became the forces of the market, almost to the exclusion of any other concerns [29].

Development of the Somborska-Studenička housing area was shaped by the following factors:

- private ownership of agricultural land on the outskirts of the city;
- strengthening of private capital, which enables the acquisition of land for construction;
- lack of detailed zoning plans in the initial phase of development (first detailed zoning plan for the area was adopted in 2004) and illegal construction;
- remnants of socialist urban planning / mismatch between the planning and implementation level (planning parameters for building block are not applicable at the level of individual building plot);
- weak institutional control of implementation of planning documents;
- investor-driven planning - modifications of planning documents aimed at legalizing the deviations in construction and adjustment to investor requirements.

These factors shaped the physical and functional structure of the area, affecting the residents' quality of life.

3.2. Physical and functional characteristics

The development of the Somborska-Studenička housing area, although formally "sketched" by planning documents, was actually shaped by investors' interpretation of the planning rules, aimed at achieving the highest possible profit. Although illegal construction on the periphery appeared in the socialist period and was tolerated by authorities as "exit" strategy in housing, it gained its full momentum in the post-socialist period. Investor urbanism reflected in the formation of privately owned individual plots with individual multi-story housing exclusively assigned to the market, without any consideration of the wider context, which led to total space fragmentation and the absence of spatial integrity [28].

Violation of planning rules

The violation of planning rules was not an individual phenomenon, but a common practice in development of Somborska-Studenička. Although it was previously planned as low-rise housing (max. number of floors GF+4), the current state in the area indicates a different development. The most common deviations include:

- exceeded number of floors – almost doubled in some parts of the area (up to GF+7), paired with construction of multistory attics (two or even three stories);
- exceeded occupancy index and floor area ratio;
- use of underground floors (basements) for residential use (see Fig. 7B);
- insufficient number of parking spaces (garages are often transformed in residential or commercial space);
- insufficient distance between building, often below the minimum allowed values not only for MH, but for any form of construction (Fig. 7);
- insufficient percentage, or even more often, total lack of green areas, etc.

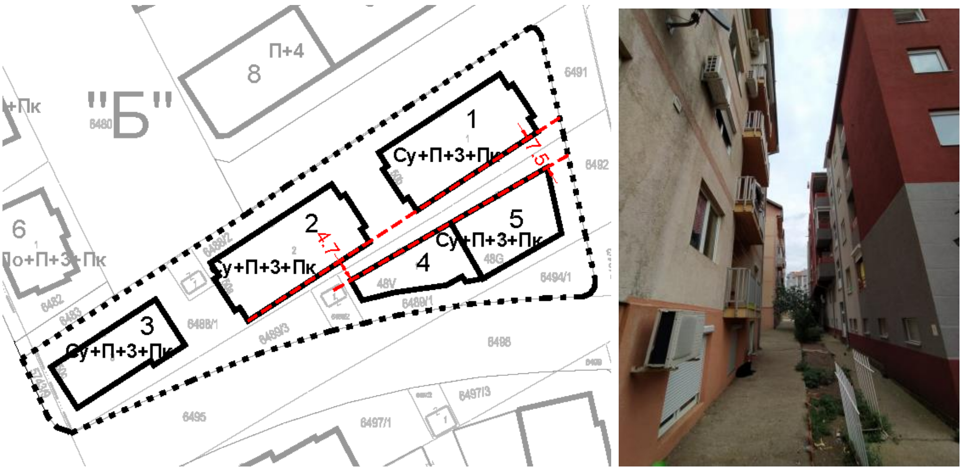

Fig. 7 Building arrangement and distance between buildings (source: authors)

Presence of such amount of deviations, indicates some additional deficiencies of planning documents, such as:

- poor definition of underground floors and their use;
- poor definition of attic and the number of attic floors - in some cases it is almost impossible to define the number of floors, since there are more attic floors;
- no distinction of green and open spaces and their use, etc.

Public open spaces and public services

The shift of power from the public to the private sector deeply affected the urban planning. Lack of public finances for the acquisition of agricultural land for public uses (public open space and public services) led to planning solutions that abolish most public uses and retain only the necessary ones, such as access streets. Streets are still considered public open spaces (POS), whereas other forms of POSs are completely ignored [28]. Somborska-Studenička area, which was primarily planned as a neighborhood unit within the GUP 1995, has been transformed into a residential and business zone by subsequent changes of GUP and DZP "Somborska-centar". Public uses (school, kindergarten, park etc.) were replaced by profitable ones - residential and commercial uses. Due to the lack of public funds, infrastructure development lagged behind the multi-family housing development financed by private capital. The internal street network, necessary for functioning of the housing area, was partially built only at the beginning of 2021. Basic public services (school and kindergarten) have been relocated by plan to the eastern, undeveloped part of the location to delay their construction. So, the housing area with more than 5,000 inhabitants develops without any form of public open /green space and basic public services.

Lack of private open/green space

Negative effects have materialized not only in the case of POS but also in the case of open spaces in general. The disappearance of open / green space is partially a result of remnants of "socialist mindset" in urban planning. Green areas were substantial part of socialist LHE, making up more than 50% of their area. That is partially a reason why in post-socialist urban plans, including DZP "Somborska-centar", green spaces were defined only formally, without binding percentage in total area of building plot. In GUP 2010 („Official Gazette of the City of Nis" No. 43/11) the percentage of open space and greenery is expressed as one (10% of building plot), there is no binding percentage of greenery, so the entire open space around the building can be paved [30], which is often the case. The planning documents oblige all investors to provide parking and open green areas within their plots. Because parking is strictly defined, and open space only formally so, in practice, open space has been completely neglected [28]. Extreme examples indicate complete disappearance of greenery at the plot level (Fig. 7).

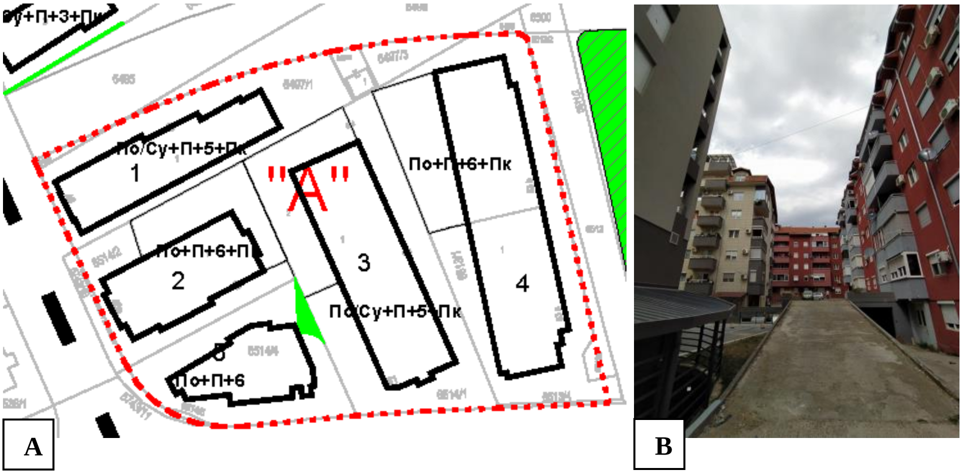

Fig 8 Greenery and open space in building block “A” (source: authors)

Organization of pedestrian and car traffic

Due to its compact urban structure, the City of Niš has managed to retain the efficient traffic network system on the entire city territory, including the suburban belt [31]. That makes the area Somborska-Studenička well connected to the city center and easily accessible, which is a good basis for further development. As opposed to well organized external street network, the internal traffic, both vehicle and pedestrian is very poorly organized. Street network is dense and composed of oversized streets dividing the area into small blocks. Due to private land ownership, blocks are organized randomly - “plot by plot”, with a criterion of maximum land utilization and with no consideration of spatial integrity and pedestrian connections (see Fig. 7 and Fig. 8). Individual development of plots caused numerous denivelations at the ground level, additionally reducing the walkability and limiting the pedestrian paths to street sidewalks only (see Fig. 8B).

Physical and functional manifestations of investor urbanism supported by planning documents can be summarized in the following:

- congestion of space caused by high occupancy level, building density, exceeded object height and insufficient distance between buildings;
- space fragmentation and absence of spatial integrity;
- lack of open /green space (public and private);
- poorly designed pedestrian and vehicle traffic patterns;
- lack of basic public services.

CONCLUSION

Transformation of urban structure is third and the longest lasting phase of post-socialist transformation. As Hirt (2012) pointed out, the following features of the transformation were especially important for cities: the return of market mechanisms and the re-commoditization of space, change of ownership patterns, a shift of control from state to local levels, a sharp increase in the number of actors participating in city-building, and a fundamentally changed role for planning [32]. Being an integral part of the urban structure, MH was also deeply affected by these changes.

Multifamily housing in post-socialist period is analyzed on the example of the City of Niš, one of the most important former industrial centers in Serbia, which undergone dramatic changes after the collapse of the socialist system. Having in mind almost complete withdrawal of public sector from housing, except small-scale projects (social housing, housing for university staff and armed forces), we can say the private sector and landownership had a decisive role in MHD in post-socialist period. Accordingly, two characteristic development phases can be distinguished. The first, initial phase is characterized by weak private sector, low availability of construction land in inner-city area due to unresolved property rights and multifamily housing development in form of MHEs and construction on greenfield sites on the outskirts of the city. Second phase is marked with the strengthening of the private sector, greater availability of construction land and the spread of different types and scale of multifamily housing to all parts of the city: infill development (mostly in socialist LHEs), reconstruction of the city center, larger-scale construction on brownfield and greenfield sites.

The analysis of the Somborska - Studenička housing area, showed that physical and functional structure of the area is largely a result of systematic violations of building rules set in planning documents, as well as deficiencies of planning documents. Investor-driven development resulted in spatial and functional fragmentation of space, loss of open and green areas (both public and private), lack of basic public services, pedestrian inaccessibility and congestion of space, affecting the quality of life of residents at the neighborhood level.

Numerous changes to the existing planning documents proved to be a bad solution because they mainly focused on specific problems, without reevaluation of overall planning concept. Namely, the changes to the plans were aimed at establishing a control over the future development of the area, but they actually legalized the existing deviations and made a basis for further abuse. It seems that the planning lagged behind the construction from the very beginning of development. Instead of development following the plan, plans usually followed the development.

The fact that section Somborska - Studenička is only a part of wider area, which is currently under the pressure of housing development, arises the need for profound changes in the way of planning. Long-term solutions need to be devised in collaboration between planners and market actors, though it is obvious that this delicate balance between planning and market forces in post-socialist circumstances in Serbia has not yet been established [33].

The authorities of the City of Niš recently launched an initiative to change the general zoning plans for the city municipalities. The most significant change compared to the existing plans could be the increase of the allowed number of stories (up to twelve or fourteen) in suitable locations, among which the Somborska area is often mentioned. Although this initiative may resemble the socialist planning of LHE, modified conditions of development must be carefully analyzed in order to avoid the effects of investor urbanism present in the built-up part of the area.

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KARAKTERISTIKE RAZVOJA VIŠEPORODIČNOG STANOVANJA U POST-SOCIJALISTIČKOM PERIODU-STUDIJA SLUČAJA, NIŠ

Rad se bavi karakteristikama razvoja višeporodičnog stanovanja (MHD) u specifičnim uslovima postsocijalističke tranzicije. Višeslojne političke, institucionalne i društveno-ekonomske promene uticale su na promenu urbane strukture gradova, uključujući i stambena područja. Vremenska distanca od trideset godina od početka tranzicije u Srbiji daje nam dobru poziciju da pratimo i u potpunosti razumemo efekte promena, uključujući poslednju i najdugotrajniju fazu tranzicionog procesa – urbane promene. Razvoj višeporodičnog stanovanja u postsocijalističkom periodu sagledan je na primeru grada Niša, tipičnog socijalističkog industrijskog grada koji je pretrpeo dramatične promene u post-socijalističkom periodu i predstavlja dobar poligon za praćenje tranzicionih promena i njihovih efekata. Cilj rada je da se prepoznaju različiti tipovi višeporodičnog stanovanja i tranzicione promene koje su dovele do određenog tipa razvoja i njihovog prostornog rasporeda u gradu. Istraživanje daje klasifikaciju tipova višeporodičnog stanovanja prema mestu razvoja, poreklu kapitala, obimu izgradnje, vremenu pojavljivanja. Istraživanje sugeriše da na razvoj višeporodičnog stanovanja posebno utiču privatizacija u početnoj fazi tranzicije, restitucija u kasnijoj fazi tranzicije, promena uloge javnog i privatnog sektora u stambenom razvoju, kao i promene u urbanističkom planiranju.

Ključne reči: *višeporodično stanovanje, urbane promene, postsocijalizam, tranzicija, Grad Niš*

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Original Scientific Paper

THE HYDROLOGICAL AND ENVIRONMENTAL ASPECT OF LOW FLOW ASSESSMENT IN UNGAUGED BASINS – A CASE STUDY IN THE JUŽNA MORAVA RIVER BASIN

UDC 556.53:532.57(497.11)

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Abstract. *Eighteen low flow indicators are considered in the research of sixteen hydrological stations in the Južna Morava river basin. The indicators are estimated by statistical analysis and grouped as hydrological and environmental indicators. A cross-correlation between all indicators is assessed. Environmental flows at hydrologic stations are obtained by the GEP method. The environmental low flow indicators are transferred to two small ungauged basins by regression with physiographic characteristics. The adjustment of environmental flows at ungauged basins is performed according to locations of the donor stations in the hydrogeological regions of the studied area.*

Key words: *low flow indicators, statistical analysis, regional analysis, ungauged basin, environmental flow, GEP method*

1. INTRODUCTION

Many applications in water resources planning and management include low-flow conditions. The main topic related to low flows is water availability, defined by quantity, quality, and location over time [1] i.e. the dynamics of water availability at the location of interest. The World Meteorological Organization, WMO [2] provides a broad list of the low-flow regimes of a river, and for each one, the analysis technique, data requirements, and some common applications. The techniques for estimating and predicting low river flows are shown for both gauged and ungauged basins. In this way, quantity and location component of the low river flow is explicitly covered, while the water quality component

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is linked to water quantity in an implicit way – there are commonly used flow variables like 95% duration daily flow (Q95 or Q95%), used to simulate downstream water quality distributions. This is a typical example of the design flow in use until the 1980s as a maintenance flow – the water resources management related flow such as the minimum guaranteed release flow for a reservoir.

A growing concern worldwide over the relationship between water and the environment, has brought the concept of environmental flow, meant for the protection of biological and social systems supported by rivers [3]. In the 1980s, the USA Environmental Protection Agency (EPA) has started differentiating the design flow methods to the ones determined by the hydrologically-based and biologically-based methods [4]. The former is independent of biological considerations, while the latter includes the actual frequency of biological exposure to continuous concentration of a pollutant, and maximum concentration in water. These criteria are used to protect aquatic life from chronic and acute harmful effects respectively. The rationale for both hydrological and biological methods is different, although both rely upon statistical analysis of gauged flows, and final results of both analyses have to be compared for the final decision on design flow. While these methods are based on gauged flows only, there are more complex methods for assessing environmental flow that incorporate water quality monitoring and data sampling over several years. Although there are many examples of successful application of such models, including MABIS model applied in the region [5], it has been observed that similar results might be obtained by simpler and less data demanding methods [6].

Tharme [7] has proposed the following classification of environmental flow assessment models: 1) Hydrological index methods, 2) Hydraulic rating methods, 3) Habitat simulation methodologies, 4) Holistic methodologies. One third of all methods belongs to the Hydrological methods category relying upon gauged flow data, therefore also called Historical Flow methods [8]. As mentioned for the EPA's recommendation [4], the flows assessed by hydrological methods have to be compared to the needs of the river ecosystem for final decision upon design flow. This requirement is well communicated in the Three-Level Framework [9], where Comprehensive hydrologic desktop models are at the Level 1, followed by the second level Expert Panel Assessment, and ending by Level 3: Examining Tradeoffs and Predicting Results of Operational Changes.

The methodology for environmental flow assessment in Serbia is not yet decided and put in power [10]. Traditionally, the following hydrologic low flow indicators have been used for the purpose: a percentage of mean annual flow (10%-15%), and 95% exceedance probability of either minimum averaged 30-day daily flow or minimum monthly flow. Đorđević and Dašić [6] have proposed the GEP method that utilizes listed traditional variables for a cold/winter season (October-March), while in warm/summer season (April-September), higher values are used: 15% and 25% of mean annual flow, and 80% exceedance probability of either minimum averaged 30-day daily flow or minimum monthly flow. The alternative for using minimum monthly flow instead of minimum averaged 30-day daily flow is recommended due to local (country) gauged hydrologic data situation, being aware of the fact, a minimum monthly flow is somewhat larger than minimum averaged 30-day daily flow.

Although rarely used, there are examples of presenting 95% (also, 90%, 80% and 50%) exceedance probability of minimum annual flow as hydrologic low flow indicators [11], [12].

The aim of this research is to assess the range of low flow variables used for environmental flow assessment, and examine its transferability to ungauged basins in the Južna Morava river basin.

The motivation for the research is concern raised due to expected impact of two greenhouse gas emission scenarios on changes in climatological and hydrological parameters in Serbia [13], adverse for both water management and environmental systems. Low flow reduction is of particular concern in the upper and middle basin parts of the Južna Morava river, the most vulnerable to potential change being the tributaries of the first and second order to the main river [10].

Two small ungauged basins are studied in this research, one of the first and one of the second order tributary to the Južna Morava river. Low flow assessment relies on background analysis on hydrogeological conditions in Hydrological studies of the Tulovska river [14] and Vujanovačka river [15]. In the low flow periods, especially in the small and medium size river catchments, the main factor influencing flow magnitude is geologic/hydrogeologic composition [16]. Gauged flow data are collected from hydrological stations with drainage basins characterized by similar hydrogeological factors, situated in the upper and middle basin parts of the Južna Morava river. In the low flow regional analysis, these are donor stations used to transfer information on low flow indicators from gauged to ungauged basins.

2. METHODOLOGY

2.1. Study area and collected data

2.1.1. Location

The study area comprises drainage basins of 16 hydrological stations (HS) shown in Fig. 1 in the Južna Morava river basin, with perimeter highlighted in yellow. The two ungauged locations are indicated by blue squares, HS by red triangles. Majority of the study area belongs to the region III, one of five hydrogeological regions defined in the South of the Danube and Sava rivers, as shown in Nikić [16].

2.1.2. Data for low flow analysis

The relevant data for low analysis in this research is time series of daily mean flow values at selected HS, in the period up to the year 2020 (Table 1). The data is published in the Hydrological Yearbooks of the Republic Hydrometeorological Service of Serbia [17]. The physiographic data for the two ungauged basins is taken from the design projects [14], [15], and catchment area for gauged basins – HS, from the Hydrological Yearbooks [17].

An initial daily flow data check has shown that gauging period at selected HS ranges from 56 to 73 years. In the gauging period, years without any data and years with incomplete data are found (Table 1).

2.1.3. Daily flow data examination

In the data examination process, two main issues are addressed: 1) deriving the datasets for statistical analysis from the daily flow time series with gaps, and 2) examining suitability of datasets for statistical analysis.

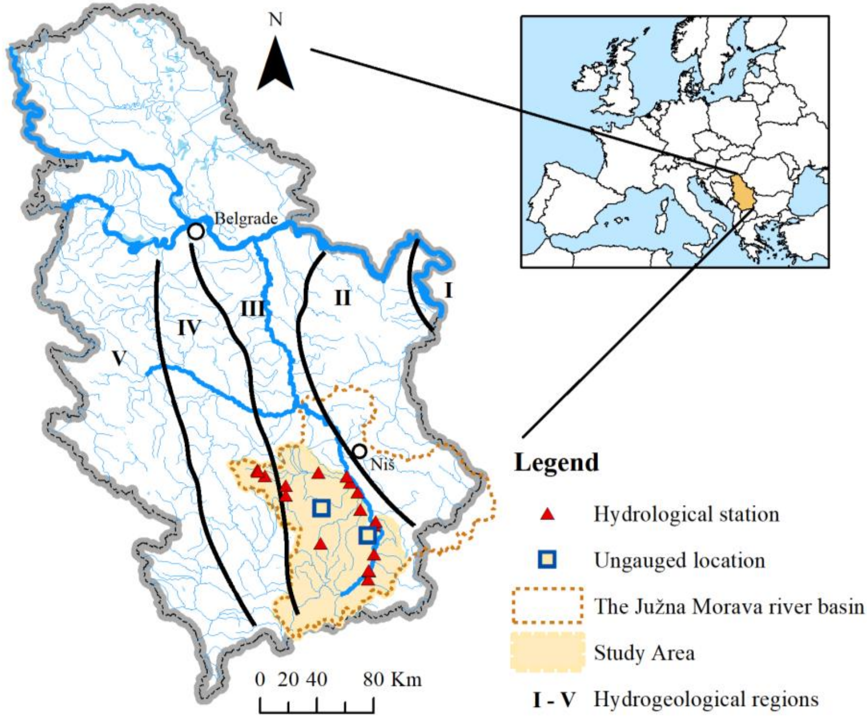

Fig. 1 Study area location in Serbia with hydrogeological regions from [16]

The following datasets are composed for low-flow investigation:

1. 30-day flow minima (Q30dMin),
2. Annual flow minima (QAnnMin),
3. Mean monthly flow minima (QMonMin),
4. Mean annual flow (QAnnAvg).

In the case the data are missing for the whole year, that year is rejected when composing any dataset. For the years with incomplete data it has been observed which part of the year is with the data gap. If the gap is located in the period July-October, the typical low flow period, that year is not included when composing any dataset. Appearance of data gaps in the period January-June and November-December is ignored for deriving 30-day minima, mean monthly minima and annual minima datasets, but not for the dataset comprising annual average flows. When ignoring missing daily data, characteristic flows are obtained from the remaining daily data in that year. The basic data processing period is a calendar year.

Suitability of the datasets for statistical analysis is examined at 5% significance level by the tests intended to detect:

1. Inhomogeneity: t/z test, F-test, Leven's test, Mann-Whitney test;
2. Trend: Mann-Kendal test, Spearman's rank test, linear trend presence test, significance test for the slope of linear regression;
3. Outliers: Grubbs and Beck test.

Table 1 The initial daily flow data check results

No. [#]	Hydrologic station (HS)	River	HS code	Start gauge [year]	Years with complete data [no.]	Years with no data [no.]	Years with incompl. data [no.]
1	Vranj. Banja	Banjska	47526	1964	56	0	1
2	Vranj. Priboj	J. Morava	47528	1948	68	5	0
3	Vlad. Han	J. Morava	47530	1949	67	4	1
4	Tupalovce	Kozarska	47539	1961	58	0	2
5	Grdelica	J. Morava	47540	1948	73	0	0
6	Sij. banja	Jablanica	47720	1965	52	4	0
7	Magovo	Toplica	47820	1958	46	16	1
8	Merćez	Lukovska	47825	1953	49	16	3
9	Donja Selova	Toplica	47830	1952	66	0	3
10	Pepeljevac	Toplica	47850	1951	70	0	0
11	Prokuplje	Toplica	47880	1951	64	4	2
12	Doljevac	Toplica	47890	1954	67	0	0
13	Pukovac	Pusta	47548	1950	67	4	0
14	Leskovac	Veternica	47665	1948	71	2	0
15	Pečenjevce	Jablanica	47740	1950	70	0	1
16	Visoka	Kosanica	47855	1960	55	2	4

When inhomogeneity or a trend is detected in the dataset, the oldest data is step by step deleted from the record and tested, until the truncated dataset becomes homogeneous and without a trend, meaning the datasets comprise the most recent data. All of the truncated datasets still have more than the minimum of 30 gauged years (the initial representativeness condition).

Outlier treatment approach applied is: High outliers are removed from the datasets, while the low ones are left in it.

Zero flows in the datasets are noted for further consideration in the statistical analysis.

The main findings and decisions in the data examination process are given in Table 2.

2.2. Low flow assessment

Two groups of low flow indicators are used in the research, one related to mean annual flow, the other to low flow quantiles assessed by statistical analysis.

Statistical analysis of low flows is performed on the *Q30dMin*, *QAnnMin* and *QMonMin* samples. Among several theoretical distributions considered [18], as illustrated in Fig. 2 for the *Q30dMin* dataset at HS Visoka, the prevailing best fit to empirical distribution (Weibull's plotting position) is Log Pearson III (LP3) distribution, according to a several criteria applied (statistical properties of sample, probability plots, Kolmogorov-Smirnov test, Cramer von Mises test, RMSE).

In the datasets with zero flows, conditional probability is applied [19]:

$$H(x) = q + (1 - q) \cdot F(x). \quad (1)$$

Here,

$H(x)$ – probability distribution function of variable x,

$F(x)$ – probability distribution function for $x>0$ only,

q – probability of $x=0$, calculated from $q=m/N$ i.e. ratio of number of zero flows (m) and sample size (N).

It should be noted that all quantiles cannot be estimated from the samples with zero flows. Therefore, at some HS, the highest exceedance probability quantiles could be absent regardless of their importance in low flow analysis. In practice, it should be checked when the condition $F(x)>0$ is met [20]. From equation (1) it is obtained that the smallest flows (the highest exceedance probability quantiles) that can be estimated correspond to the probability $H(x)=q$.

Table 2 The data examination review

No. [#]	Hydrologic station (HS)	Sample start [year]	Sample size of Ann Avg dataset [no.]	Data gap duration [year (days)]	Ignored data gap in year [year]	Sample size of AnnMin, 30dMin and MonMin dataset [no.]
1	Vranj. Banja[1]	1977*	43	2016 (99), 2016 (9)	-	43
2	Vranj. Priboj	1948	68	-	-	68
3	Vlad. Han	1949	67	2018 (47)	2018	68
4	Tupalovce	1977*	42	1993 (26), 2015 (92)	1993, 2015	44
5	Grdelica	1948	73	-	-	73
6	Sij. banja	1982*	36	-	-	36
7	Magovo	1958	46	2006 (165)	2006	47
8	Merćez	1953	49	2006 (165), 2008 (158), 2015 (42)	2006, 2015	51
9	Donja Selova	1977*	41	1990 (92), 2018 (28), 2019 (56)	2018, 2019	43
10	Pepeljevac	1984*	37	-	-	37
11	Prokuplje	1951	64	2019 (82), 2020 (112)	-	64
12	Doljevac	1954	67	-	-	67
13	Pukovac[0]	1961*	57	-	-	57
14	Leskovac[0]	1955*	50	-	-	50
15	Pečenjevce[0]	1982*	34	1990 (59)	1990	35
16	Visoka[0]	1980*	35	1992 (31), 2015 (30), 2019 (35), 2019 (42), 2020 (30), 2020 (27)	1992, 2015	37

* - truncated dataset; 1 – high outlier detected in any dataset; 0 – zero flow(s) in any dataset

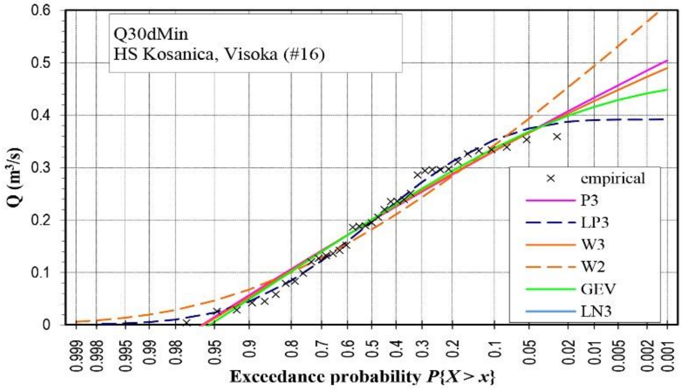

Fig. 2 Probability plot of the *Q30dMin* sample at HS Visoka (no. 16)

2.3. Environmental flow assessment

Environmental flow is assessed by the GEP method [6], based on the comparison of 30-day minima (*Q30dMin*) quantile to the lower and the upper threshold – a percentage of mean annual flow (*QAnnAvg)*, depending on the season. The assessment procedure is given in the form of logical test – IF (logical test, value if true, value if false).
Winter flow:

$$QEnv = IF(Q30dMin, 80\% < 0.1 \cdot QAnnAvg, 0.1 \cdot QAnnAvg,$$
$$(IF(Q30dMin, 80\% > 0.15 \cdot QAnnAvg, 0.15 \cdot QAnnAvg, Q30dMin, 80\%))) \quad (2)$$

Summer flow:

$$QEnv = \mathrm{IF}(Q30dMin, 95\% < 0.15 \cdot QAnnAvg, 0.15 \cdot QAnnAvg,$$
$$(\mathrm{IF}(Q30dMin, 95\% > 0.25 \cdot QAnnAvg, 0.25 \cdot QAnnAvg, Q30dMin, 95\%))) \quad (3)$$

2.4. Regional analyses

The models based on regional analysis are selected for transfer of low flow indicators from donor stations – sixteen HS, to two ungauged basins. In general, the transfer is eligible within a hydrological homogeneous region. In this research, it is assumed that the homogeneity condition is met by the prevailing location of the donor catchments in the hydrogeological region III (Fig. 1) for the selected low flow model. In the case of the mean annual flow assessment model, homogeneity is confirmed in the original research [21]. In addition, a cross-correlation matrix is generated using all of the low flow indicators assessed for donor stations and the catchment area.

2.4.1. Low flow

In the hydrogeological homogeneous region, the following relations may be established according to Vladimirov's method [22]:

$$Q30dMin, 80\% = f_1(A), \quad (4)$$

$$Q30dMin, 95\% = f_2(Q30dMin, 80\%) \quad (5)$$

where:

A – catchment area (km^2),

Q30dMin,80% – 30-day minimum flow of 80 % exceedance probability (m^3/s),

Q30dMin,95% – 30-day minimum flow of 95 % exceedance probability (m^3/s).

The procedure of Vladimirov's incorporates the following steps:

- Selection of donor stations (HS) to use the data for the regression model;
- Low flow statistical analysis for selected HS to obtain required flow quantiles;
- Development of linear regression models (4) and (5), where both independent and dependent variables are logarithmic transformations of original data.

2.4.2. Mean flow

On the sample of 184 catchments, Živković [21] has established a set of region-specific regression models for mean annual runoff estimation based on precipitation data in the period 1951-1980 and runoff in the period 1961-1990. The regional regression equations are variable-specific and region-specific. The form of the established equation that uses physiographic characteristic – mean catchment altitude, is used here.

According to the regression equation for the region 8 – 'Južno Moravski' [21]:

$$ln\ q\ = 1.47 + 0.001 \cdot Xsr\ , \qquad (6)$$

where:
q - specific runoff -mean annual runoff per unit catchment area (l/s/km^2)
Xsr - mean catchment altitude (masl - m above sea level).

Applied to the Tulovska river, ungauged basin I, equation (6) yields q = 6.68 l/s/km^2, i.e. mean annual flow Q = 0.139 m^3/s [14]. In the ungauged basin II of the Vujanovačka river, q = 6.578 l/s/km^2, and Q = 0.244 m^3/s [15].

2.5. Low flow indicators

A total of eighteen low flow indicators is considered in the research for each HS (Table 4). One set of indicators is merely hydrological, the other related to environmental flow. Fifteen indicators are low flow quantiles (50%, 70%, 80%, 90% and 95% exceedance probability) estimated by statistical analysis of three datasets: *Q30dMin*, *QAnnMin* and *QMonMin*. Three indicators are calculated based on *QAnnAvg* assessment (10%, 15% and 25% of it).

The left pane in Fig. 3 shows the selection scheme of low flow indicators for environmental flow according to the two key criteria by the EPA [4]. *Q1dMin,90%* and *Q7dMin,90%* are hydrological indicators that have to be compared to the needs of the river ecosystem expressed through 'B' (biological) flows for the final decision upon design flow. Focusing on hydrological indicators in the research, *Q1dMin,90%* is selected as a representative variable among lower extremes in the low flow indicators set. *Q1dMin,90%* is interpreted as *QAnnMin,90%* quantile here, because the difference has not been found during the data examination process in the gauged flows between mean daily flow in the day of annual minima occurrence and an instant annual minima flow.

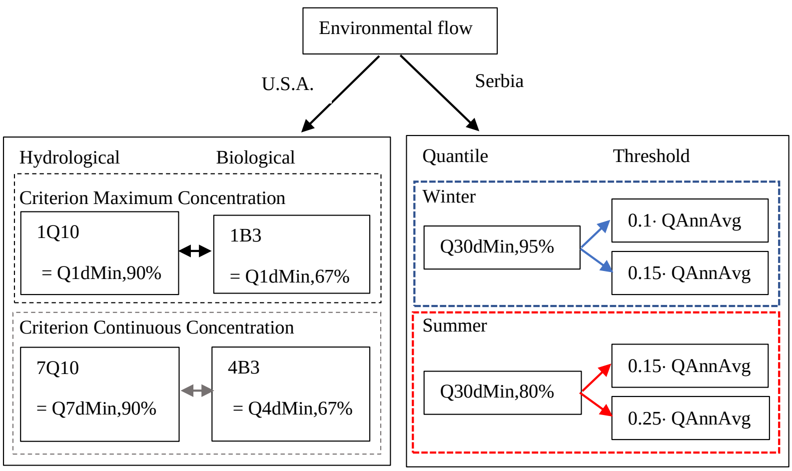

Fig. 3 The low flow indicators used in environmental flow assessment according to EPA (U.S.A.) and GEP (Serbia) methodology.

In the right pane of Fig. 3, the scheme for environmental flow selection according to the GEP method is presented, as explained in the section 2.3. The low flow indicators shown in the boxes are referred to as environmental flow related indicators, with addition of *QAnnMin,90%* quantile used in the EPA procedure.

Table 4 Low flow indicators considered in the research. Environmental flow related indicators are highlighted in blue.

No.	1	2	3	4	5
Ind.	*QMonMin,50%*	*QMonMin,70%*	*QMonMin,80%*	*QMonMin,90%*	*QMonMin,95%*
No.	6	7	8	9	10
Ind.	*QAnnMin,50%*	*QAnnMin,70%*	*QAnnMin,80%*	*QAnnMin,90%*	*QAnnMin,95%*
No.	11	12	13	14	15
Ind.	*Q30dMin,50%*	*Q30dMin,70%*	*Q30dMin,80%*	*Q30dMin,90%*	*Q30dMin,95%*
No.	16	17	18		
Ind.	*0.10·QAnnAvg*	*0.15·QAnnAvg*	*0.25·QAnnAvg*		

3. Results and Discussion

3.1. Low flow indicator range

A general review of all eighteen low flow indicators at studied HS is shown in Fig. 4 and Fig. 5 by the box plots. The actual values of flows or statistics are not important, but the spread of flows/specific flows and its relative standing to the adjacent group of HSs. The box plots are arranged according to the catchment area in the ascending order.

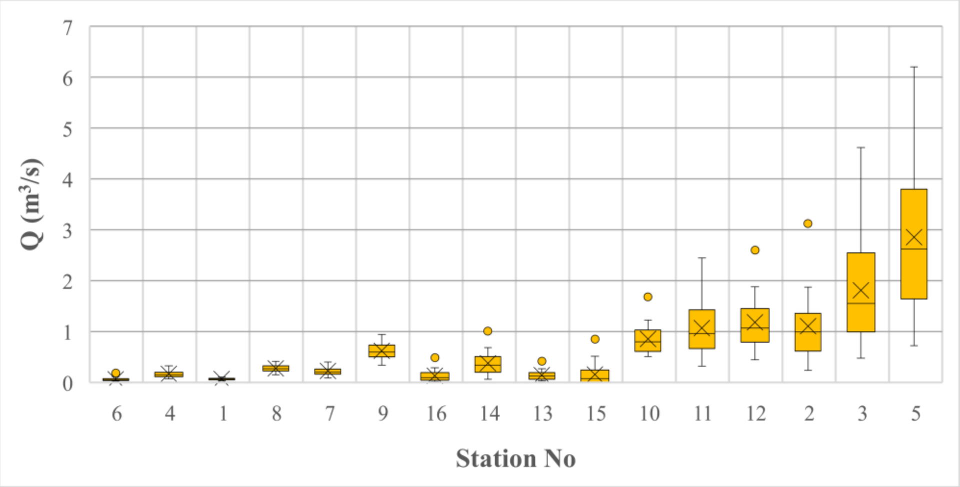

Fig. 4 The range of low flow indicators (flows) at HS ordered by ascending catchment area

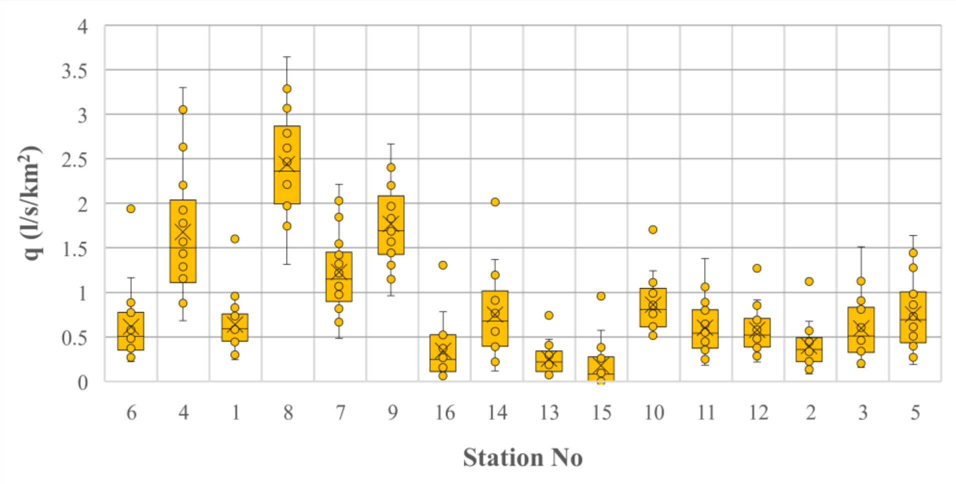

Fig. 5 The range of low flow indicators shown as specific runoff at HS by catchment area in ascending order

Both gradual rise of the box positions in Fig. 4 and gradual fall in Fig. 5 is expected. The HSs that behave differently in both Fig. 4 and Fig. 5 (the central part) are no. 16, 14, 13 and 15. These are the HS with zero flows in the *QAnnMin* datasets, while HS no. 15 also has zero flows in the *QMonMin* and *Q30dMin* datasets. Due to a large number of zero flows at that station, some low flow quantiles (*QMonMin,95%; QAnnMin,90%; QAnnMin,95%* and *Q30dMin,95%*) could have not been assessed. Instead, the flow of 0.0001 m^3/s is used for the calculation sake.

Among the HSs with small catchment area (95-180 km^2), stations no. 6, 4, 1 and 7 seem too low with both flows and specific flows. They are on the left side in Fig. 4 and Fig. 5. Station no. 6 is upstream from the no. 14 with zero flows, being poor in water. Stations no. 4 and 1 are on the first order right tributaries to the Južna Morava river. It is interesting that in Živković's research findings [21], stations no. 1, 2, 3 and 4 belong to the same region for the mean annual runoff assessment. HS no. 7 is one of the stations protruding to the hydrogeological region IV in Fig. 1. However, stations no. 8 and 9 also do, but have higher flows. A different behavior of the station no. 7 from the whole set of HSs considered is also highlighted by the fact that it is the only station where LPT3 distribution could have not been used for quantile assessment but LN3 for the QAnnMin dataset.

3.2. Low flow indicator and catchment area correlation

Correlation between seventeen variables is examined, fifteen variables are low flow indicators 1 -15 in Table 4, sixteenth is *QAnnAvg*, and seventeenth, catchment area (*A*). Fig. 6 shows output - a scatter plot of matrices, with bivariate scatter plots below the diagonal, histograms on the diagonal, and the Pearson correlation coefficient above the diagonal. Correlation ellipses are also shown. Robust fitting is done using LOWESS (locally estimated scatterplot smoothing) regression. The flow values are converted to l/s and log transformed – these values are reported as well as log transformed values of the catchment area.

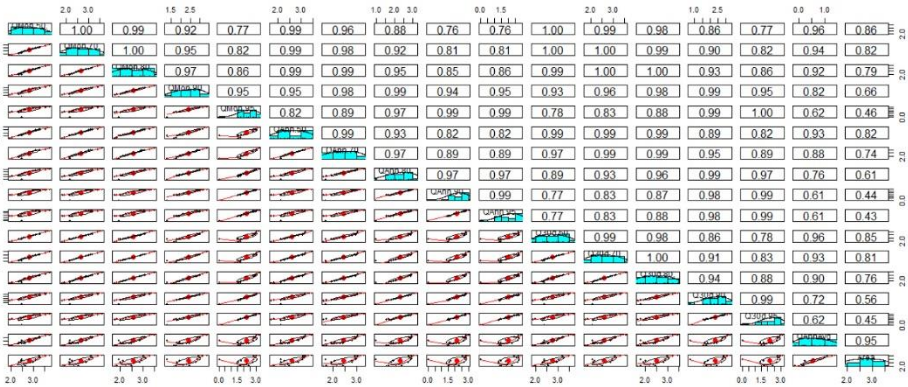

Fig. 6 Correlation among low flow indicators and catchment area

Correlation among the variables used in the GEP method, EPA method, and catchment area is shown in Fig. 7. The strongest correlation is exhibited between *QMonMin,80%* and *Q30dMin,80%*, *QMonMin,95%* and *Q30dMin,95%* providing for assessment of Q30dMin when instead of daily, monthly flows are available. Then, *QAnnMin,90%* and *Q30dMin,95%* are also strongly correlated, and most importantly, QAnnAvg and catchment area, allowing assessment of the thresholds in the GEP method in ungauged basins.

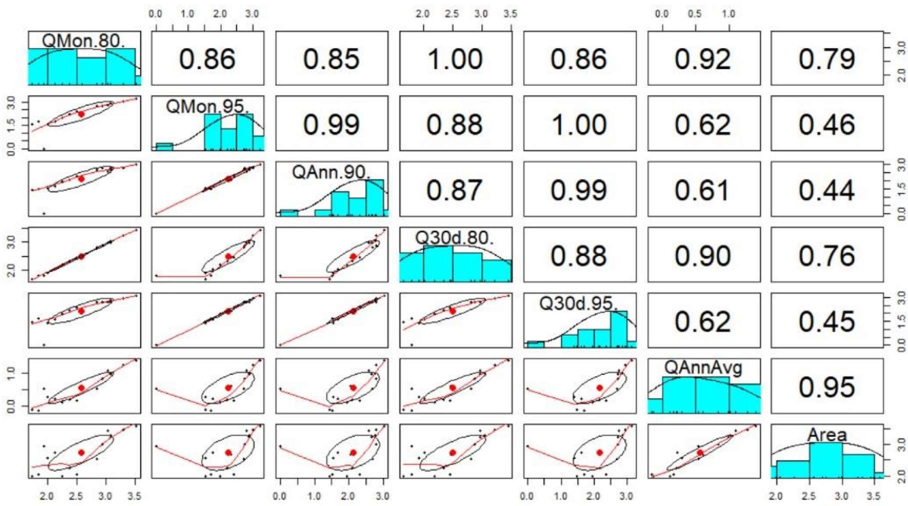

Fig. 7 Correlation among the environmental flow related indicators and catchment area – an excerpt from the 17 x 17 matrix shown in Fig 6.

3.3. Environmental flow at HS

The low flow indicators that are constitutive elements in the environmental flow assessment by the GEP method in the winter and summer period are shown in Fig. 8 and Fig. 9 respectively. The environmental flows are presented by the squares, while the EPA methodology variable, the same for both winter and summer period - *QAnnMin,90%*, is also shown in Fig. 8 and Fig. 9. The same variable types are connected by lines for better perception of their order throughout HS, represented by catchment area. The actual values of all low flow indicators from the group related to environmental flows are shown in Table 3. The values adopted for environmental flow *QEnv* are highlighted in blue for the winter period, and in red for summer.

In all stations but no. 8 and no. 9, the environmental flow according to the GEP method equals the lower threshold, meaning the corresponding low flow quantile is below it. In the majority of the HS, *QAnnMin,90%*, is the lowest flow, followed by the *Q30dMin* and *QMonMin* quantiles, exhibiting strong correlation among each other as shown in Fig. 7. The correlation of *QAnnMin,90%* is stronger to the 95% than 80% quantile.

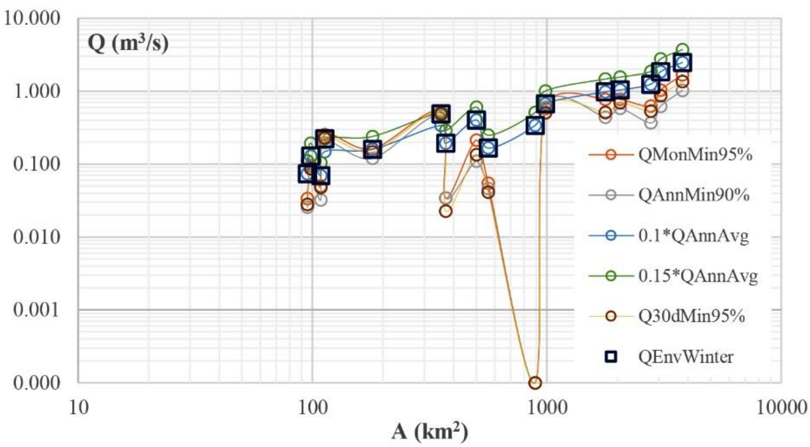

Fig. 8 Winter environmental flow and associated low flow indicators

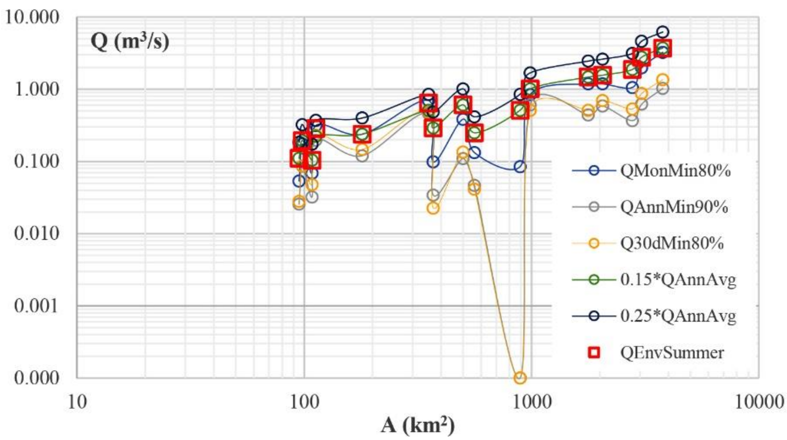

Fig. 9 Summer environmental flow and associated low flow indicators

At HS no. 15, there are 7, 4 and 3 zero-flows in the *QAnnMin*, *Q30dMin* and *QMonMin* datasets respectively, presenting the case when quantiles cannot be estimated from the samples with zero flows due to the unmet condition $F(x)>0$ as explained in 2.2.

In the stations no. 8 and no. 9, *QEnv* is higher than the lower threshold both in the winter and summer period. These are the stations from the hydrogeological region IV (Fig. 1), and higher flows found in these stations is discussed in 3.1.

Table 3 Environmental flow assessed by the GEP method at HS ordered by catchment area

No	HS	A	*Q30dMin80%*	*Q30dMin95%*	*0.1*QAnnAvg*	*0.15*QAnnAvg*	*0.25*QAnnAvg*	QEnv Winter	QEnv Summer
[#]		[km²]	[m³/s]	[m³/s]	[m³/s]	[m³/s]	[m³/s]	[m³/s]	[m³/s]
6	S. Banja	95	0.046	0.028	0.074	0.110	0.184	0.074	0.110
4	Tupal.	98.1	0.154	0.087	0.129	0.194	0.324	0.129	0.194
1	V. Banja	108	0.063	0.048	0.069	0.104	0.173	0.069	0.104
8	Merćez	113	0.287	0.230	0.148	0.222	0.370	0.222	0.287
7	Magovo	180	0.219	0.147	0.159	0.239	0.399	0.159	0.239
9	D.Selova	353	0.646	0.487	0.339	0.509	0.848	0.487	0.646
16	Visoka	370	0.083	0.023	0.193	0.290	0.483	0.193	0.290
14	Leskovac	500	0.294	0.135	0.403	0.604	1.007	0.403	0.604
13	Pukovac	561	0.105	0.041	0.166	0.249	0.415	0.166	0.249
15	Pečenj.	891	0.063	0.000	0.341	0.511	0.852	0.341	0.511
10	Pepelj.	986	0.747	0.508	0.672	1.008	1.680	0.672	1.008
11	Prokup.	1774	0.926	0.509	0.979	1.469	2.448	0.979	1.469
12	Doljevac	2052	1.099	0.698	1.041	1.561	2.602	1.041	1.561
2	V. Priboj	2775	0.927	0.534	1.248	1.872	3.119	1.248	1.872
3	V. Han	3052	1.651	0.869	1.848	2.771	4.619	1.848	2.771
5	Grdelica	3782	2.765	1.355	2.480	3.721	6.201	2.480	3.721

3.4. Low flow indicators transfer to ungauged basins

The regression models employed for the transfer of environmental flow related low flow indicators by the method of Vladimirov's are shown in Fig. 10 and Fig. 11. Station no. 15 is excluded from the modelling due to the zero-flow issue in the dataset *Q30dMin*. The points representing stations (empirical points) are labelled according to the station number, while ungauged locations are labelled I and II (I - the Tulovska river, II - the Vujanovačka river).

In Fig.10, stations no. 8 and no. 9 are on the upper side of the regression line, between the upper confidence limit and prediction limit, while stations no.13 and no.16 lie in the lower belt between the lower confidence limit and the prediction limit. In Fig. 11, stations no. 1, 7, 8 and 9, are upper, only no. 16 is lower.

In the case when regression model is applied on the *QAnnAvg* and *A* variables, a different behavior of stations is exhibited in Fig. 12. Here, stations no. 4, 8 and 9 are in the upper belt, while no. 16 and 15 are in the lower belt, and station no. 13 is almost out of the prediction interval lower limit.

While stations no. 13, 15 and 16 are expectedly in the lower belts, stations no. 8 and 9 in the upper (Fig. 10 – Fig. 12), stations no. 1 and 7 (Fig. 11) and no. 4 (Fig. 12) point out to a different behavior during low-flow and mean-flow regime compared to other stations in the study area.

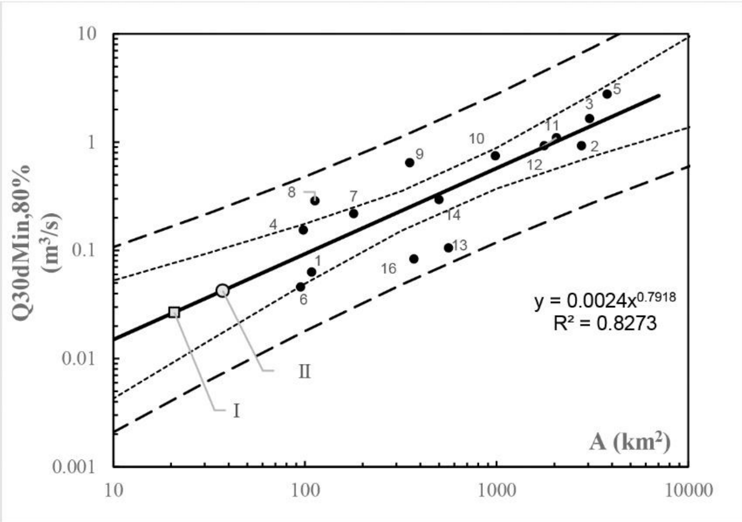

Fig. 10 Regression line according to eq. (4), 95% confidence interval (dotted lines) and Prediction interval (dashed lines); Ungauged locations are I and II

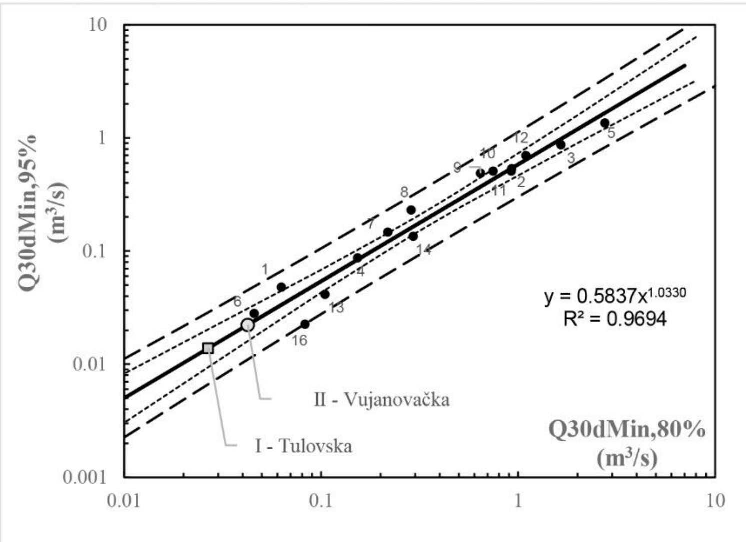

Fig. 11 Regression line according to eq. (5), 95% confidence interval (dotted lines) and Prediction interval (dashed lines); Ungauged locations are I and II

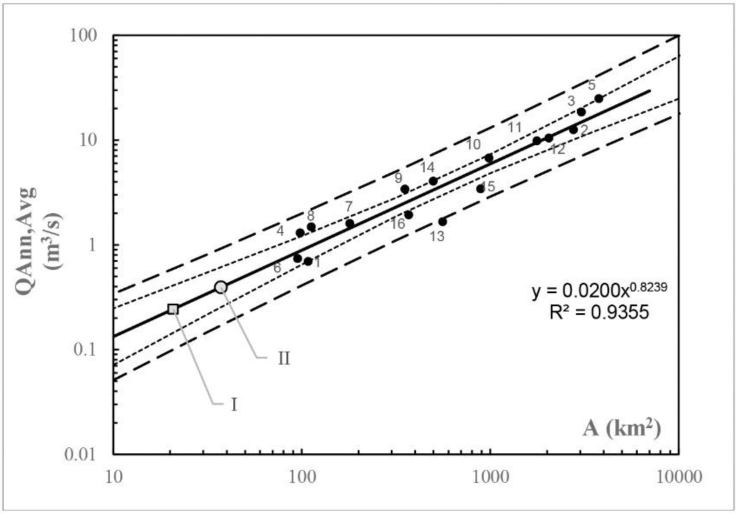

Fig. 12 Run 1: Regression line for *QAnnAvg* = f(*A*) in the studied region, 95% confidence interval (dotted lines) and Prediction interval (dashed lines); Ungauged locations are I and II

3.5. Environmental flows assessed in ungauged basins

Based on the *Q30dMin 80%* and *Q30dMin 95%* low flow quantiles assessed by the Vladimirov method at both ungauged basins, *QAnnAvg* from both regression with catchment area (Fig. 12), and from the regional equation (6), environmental flow is determined by the GEP method (Table 3).

The difference in environmental flows obtained using the *QAnnAvg* values from the regression equation in Fig. 12 for the study area is -40% for the winter flow and -30% for the summer flow, compared to the ones assessed from the regional equation using mean catchment altitude as predictor variable [21].

Table 3 Environmental flows in two studied ungauged basins, run 1

Location	A [km^2]	Q30dMin80% [m^3/s]	Q30dMin95% [m^3/s]	QAnnAvg [21] [m^3/s]	QAnnAvg regression, r. 1 [m^3/s]	QEnv - [21] Winter [m^3/s]	QEnv - [21] Summer [m^3/s]	QEnv – regr.1 Winter [m^3/s]	QEnv – regr.1 Summer [m^3/s]
I	20.8	0.026	0.014	0.139	0.244	0.014	0.027	0.024	0.037
II	37.2	0.042	0.022	0.244	0.394	0.024	0.042	0.039	0.059

Due to the significant differences between the assessed environmental flows, and previous research results related to mean flow of the Tulovska river - ungauged location I [23], a new regression model of *QAnnAvg* and catchment area is estimated (Fig. 13).

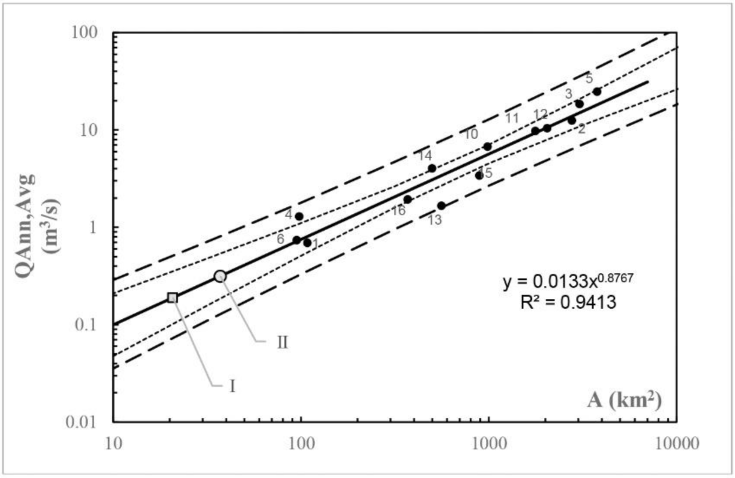

Fig. 13 Run 2: Regression line for *QAnnAvg* = f(*A*) in the studied region without stations no.7, 8 and 9; 95% confidence interval (dotted lines) and Prediction interval (dashed lines); Ungauged locations are I and II

Stations no. 7, 8 and 9 are not considered in this model (run 2), as the stations from the hydrogeological zone IV, exhibiting different behavior in many investigated low flow aspects so far.

The difference in environmental flows obtained using the *QAnnAvg* values from the regression equation in Fig. 13 for the study area dropped to -25 % for the winter flow and -8 % for the summer flow, compared to the ones assessed by the equation (6), as shown in Table 4.

Table 4 Environmental flows in two studied ungauged basins, run 2

Location	A	Q30dMin80%	Q30dMin95%	QAnnAvg [21]	QAnnAvg regression, r. 2	QEnv - [21] Winter	QEnv - [21] Summer	QEnv – regr.2 Winter	QEnv – regr.2 Summer
	[km²]	[m³/s]	[m³/s]	[m³/s]	[m³/s]	[m³/s]	[m³/s]	[m³/s]	[m³/s]
I	20.8	0.026	0.014	0.139	**0.190**	0.014	0.027	**0.019**	**0.029**
II	37.2	0.042	0.022	0.244	**0.316**	0.024	0.042	**0.032**	**0.047**

4. CONCLUSION

A set of low flow indicators comprising eighteen hydrologically based variables is assessed by statistical analysis of four datasets. Sixteen investigated hydrologic stations belong to the upper and middle part of the Južna Morava river basin. Environmental flow is assessed at each station by the GAP method - the hydrological index method. In the regional analysis procedure, regression models are applied for the transfer of low flow indicators to two small catchment area ungauged locations, where the environmental flows are also assessed.

The following is concluded:

1. Too many zero flows in the dataset may preclude quantile estimation. A practical approach is applied here – a flow of 0.0001 m^3/s is assigned for such a quantile in the cases an absence of value would prevent a larger scale estimation like cross-correlation. Otherwise, stations having such quantiles are deleted from the set of donor stations, like in the method of Vladimirov's. For any further more detailed research, other options of zero-flow treatment should be considered, like in drought studies [24].
2. An examination of the low flow variables range prior to analyses is informative. Here, it was shown that some stations stand out from the others, therefore rising awareness about potential issues in the assessed environmental flows at ungauged basins.
3. Any hydrogeological information is helpful in low flow research. Even a macro-scale hydrogeological regionalization used here [16] has improved the final assessment of environmental flows by signaling on the need to eliminate stations located in the other region from the set of donor stations.
4. It is possible to switch between low flow indicators in the absence of daily flow data. A cross-correlation matrix of the low flow indicators and catchment area shows there is a strong correlation between some of the considered variables.
5. In the studied region of the Južna Morava river basin, the GEP method for environmental flow assessment may be based on the mean annual flow only. The environmental flows (winter and summer ones) assessed for the stations in the hydrogeological region III, correspond to the lower threshold values, a portion of the mean annual flow.
6. It appears that not only minimum monthly flow quantile can be used as an alternative to 30-day minimum flow quantile in the GEP method, but the minimum annual 90% quantile as well.
7. Knowing mean flow in ungauged basin is important for low flow regime. The regional equations for mean annual flow assessment developed by Živković [21] are recommended.

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HIDROLOŠKI I EKOLOŠKI ASPEKT PRORAČUNA MALIH VODA U NEIZUČENIM SLIVOVIMA – STUDIJA SLUČAJA U SLIVU JUŽNE MORAVE

U radu je razmatrano osamnaest pokazatelja malih voda u šesnaest profila hidroloških stanica u slivu Južne Morave. Pokazatelji su ocenjeni statističkom analizom i grupisani u hidrološke i ekološke pokazatelje. Sračunata je korelacija između svih pokazatelja. Ekološki protoci u profilima hidroloških stanica dobijeni su metodom GEP. Pokazatelji malih voda su prebačeni na dva neizučena profila korišćenjem regresije sa geo-morfološkim karakteristikama sliva. Podešavanje vrednosti ekološkog protoka u neizučenim profilima urađeno je na bazi pripadnosti slivova donora hidrogeološkim regionima u izučavanoj oblasti.

Ključne reči: *pokazatelji malih voda, statistička analiza, regionalna analiza, neizučen sliv, ekološki protok, GEP metoda*

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CONDITION ASSESSMENT AND STRUCTURAL REHABILITATION OF THE ST. NICHOLAS CHURCH IN CRNA TRAVA

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Abstract. *The paper analyzes the structural condition of the church dedicated to Saint Nicholas, which is located in the town of Crna Trava, in the south of Serbia. An architectural analysis of the observed structure is provided, as well as an overview of previous works on it, both research and rehabilitation and conservation. A detailed analysis of the structural system of the church is presented. The analysis and classification of the observed damages was performed, the works on the rehabilitation of the building were presented, and a proposal of further remedial measures was given with the aim of preventing further deterioration of the building.*

Key words: *barrel vault, damage, degradation, church, rehabilitation*

1. INTRODUCTION

The paper presents the church dedicated to St. Nicholas, which is located in the town of Crna Trava, the center of the municipality of the same name located in southern Serbia. According to most sources, the building was built during the 17th century. During its service life, and due to various cultural, political and economic changes that took place, the church building underwent certain changes. Rehabilitation works were carried out on several occasions, and during one of the stages of these works, static conditions changed over the vault of the church, which caused the appearance of a large number of cracks and fissures on it. The paper presents the recorded damages, which are classified according to the types of causes that led to their occurrence. The works on the rehabilitation of the structure performed during 2021 are presented. Also, a proposal of remedial measures was given in order to prevent further deterioration of the building.

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2. Description of the St. Nicholas Church Structure

The church complex of Saint Nicholas in Crna trava is located at the very entrance to the town, from the direction of Leskovac, on the left bank of the river Vlasina. The church yard is surrounded by a stone wall. The entrance to the port is on the north side, through a monumental stone gate. The church was built on a flat plateau above which, on the west and northwest sides, there is a somewhat steeper area which still has the role of a cemetery. The bell tower is located south of the church building, as well as the remains of the foundations of the destroyed parish home [1]. During 2020 and 2021, a new parish home was built on this place, for dual purposes. In addition to the multipurpose space intended for gathering believers, the building also contains living space intended for the priest.

The years of construction of the church are mentioned in 1565 and 1636. It was built by the local population, widely known Crna Trava builders. It is a single-nave church measuring 15x8 m. To the east is a semicircular apse on the outside and inside. The narthex on the west side was added in 1807-1808. year [1]. The nave is vaulted with a barrel vault, while above the apse there is a semi dome.

The main entrance to the church, which is not in use today, is on the west side, in the longitudinal axis of the building. There are two more doors in the north wall of the church. One is located in the north wall of the narthex, along the northwest corner of the building, while the others are placed centrally, in the middle of the nave. This door is today the main entrance to the church. During the life of the building, at one point the door was broken through on the south wall, near the altar space, which was walled up during the repair works [1, 2]. The interior of the church is covered with fresco paintings.

The church is built of stone, and the finish is mortar. After numerous renovation works, today the stone is visible on the north and west facades, with bagged joints, while the south and east facades are plastered and painted in ocher-beige shade. The roof covering was initially made of stone slabs, later of ceramide, and today it is a folded tile.

On the territory of the municipality, this is one of the most important buildings registered by the Institute for the Protection of Cultural Monuments as a building with monumental properties. The procedure of declaring this facility an immovable cultural property is in progress.

3. Historical Survey

The present day appearance of the building is the result of numerous renovations that it has undergone over time. The first renovation of this building was done at the beginning of the 19th century, 1807-1808. In the part of the literature that concerns the history of Crna Trava, these years are even referred to as the years of building the church, and not renovating it [2]

For a number of years, the local population did not show interest in rebuilding the church, so it was almost completely ruined and neglected. In one period, it was even used as a dwelling for the socially challenged population, and in an even more extreme case, as cattle barn. After the Second World War, the frescoes in the church were significantly damaged, when the frescoes were first roughly chipped, plastered, and the interior of the church was painted blue. Later, in 1988, Crna trava was hit by a great flood. On that occasion, due to the river Vlasina flooding outside its riverbed, the church yard gate remained under a thick layer of silt, which covered the lower parts of the church walls.

According to the documentation of ZZSK Nis, the first serious research and conservation-restoration works were carried out right after this flood, 1989-1993. After these works, the church regained its main function after a long time, that is, it was again put to use for worship.

During 1989, in addition to probing archeological works, works on cleaning the facade, making part of the sidewalk, reconstruction of the roof cornice were carried out, and the roof covering – ceramide was partially renewed. In the stage of works in 1990-1991, inadequate and subsequently added arches and pilasters in the narthex were removed, braces were added in the upper part of the building and thus static strengthening of the upper structure was performed, facade and window openings were treated, gutters were installed, sidewalk on the west and south side, a protective retaining wall on the west and part of the south side, as well as part of the fence wall on the southeast corner of the complex were constructed. During the stage of works in 1991-1993, the complete fence wall, entrance gate was completed, part of the gate along the fence wall was leveled, the portal of the southern door of the nave was reconstructed, and the entrance door of the church was made [1, 3].

Twenty years after the last works on the church, since 2012, works on the building have been carried out again, this time without cooperation with the competent Institute for the Cultural Heritage Protection. The roof was renovated, then the floor and the iconostasis, the openings were glazed, a new chandelier was installed, as well as the necessary inventory for the service. Since 2012, the church has been in function again. In 2020 and 2021, rehabilitation works were carried out to solve the drainage of water around the church (Fig. 1).

Fig. 1 The St. Nicholas church in Crna Trava (photo: P. Petronijević)

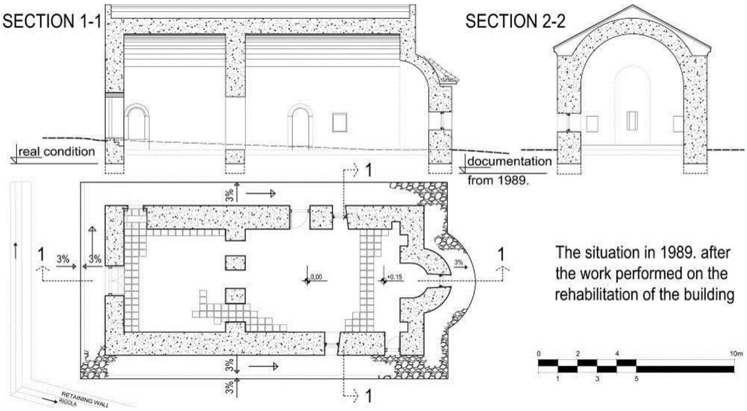

Fig. 2 Plan at the floor level, b) cross-section of a middle bay, condition from 1989, according to the documentation of ZZSK Niš

4. Description of the Structure – Structural Characteristics of the Building

The supporting structure of the church consists of bearing stone walls, about 100 cm thick. The windows are small in size and have flat end. Until the excavation of the probe pits in 2021, it was assumed that there were foundation strips under the walls, also made of stone, which were partially underpinned during the reconstruction in the period 1989-1991. The excavations determined a deviation in the depth of the foundation of the church walls in relation to the existing technical documentation of the ZZSK Nis from 1989. The depth of the foundation was on average 70 cm, and in relation to the available documentation, it is 50 cm smaller. Expansion of the walls in the form of foundation strips was not observed, as well as traces of previous underpinning of the foundations.

Above the entire building of the church, above the narthex and the nave is a barrel vault of stone. Above the vault is a wooden roof structure, with an inclination of about 30 degrees, in the form of a gabled roof, above which is a roof covering. The original stone covering was replaced with ceramide laid in crossbreed mortar, which was replaced during the last reconstruction with a folded tile placed on a wooden substructure. On that occasion, the method of supporting the roof on the vault structure was changed. The level of the roof planes was raised and tin flashing was added to the gable walls. The reactions of the vault are transmitted to the side walls, and due to the large horizontal forces that occur with such a system, metal braces were subsequently placed, in order to prevent the walls from spreading apart [4].

By a chronological analysis of the documentation of ZZSK Nis about the church, and based on the assessment of the condition of the wall masses of the church, it can be concluded that occasional and partial works on the rehabilitation did not give satisfactory results. After certain works in 1989, many years of complete neglect ensued. Thus, certain parts of the wall masses and the entire vault were brought into poor condition. So the church required significant reconstruction work.

5. Observed Damage to the Building

The assessment of the condition of the building was performed on the basis of a detailed visual inspection of the walls, vaults and roof structure. The walls were analyzed separately for direction. The outer and inner surfaces of the walls were observed, with the aim of locating places where there is a possibility of cracks propagating through the entire thickness of the wall [5]. Based on the collected data, the causes of cracks are defined and their further evolution is predicted. A comparison of crack maps in relation to the situation from 2017 was performed and critical causes of crack progression were defined. The cracks in the structure are, as a rule, a reflection of: the main stresses in it, the balance of internal forces, and the disturbances that have occurred in it over time. For this reason, significant data were obtained from monitoring damage propagation over time. This was done on the example of this facility after five years' time. During that period, the development of signs of instability was monitored, the phenomena of damage were interpreted and described, and the causes of their occurrence were identified.

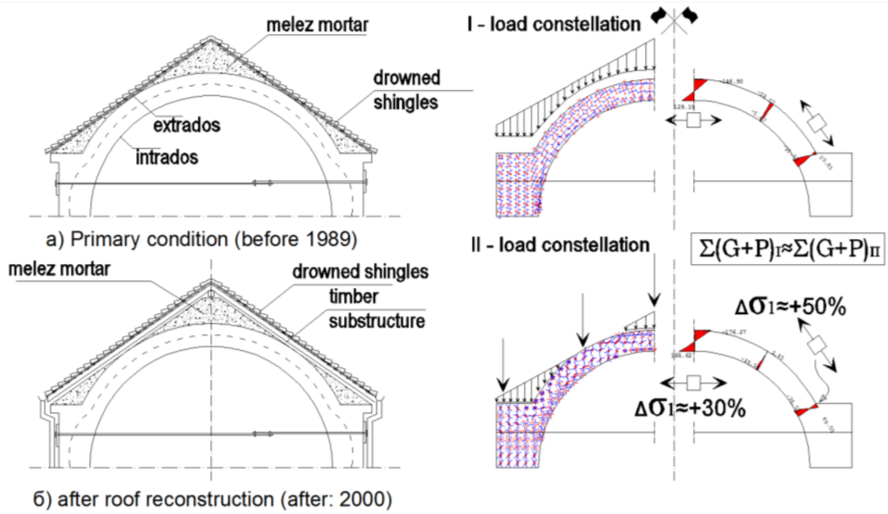

Fig. 3 Change of stress state in the vaults after the self-initiated reconstruction of the roof by the church board, (drawing: P. Petronijević).

The masonry construction of the church proved to be relatively stable, taking into account the time of its construction. Since the building is built of materials with a porous structure, the influence of moisture and frost is the dominant deterioration factor in the ground level parts of the walls. Inadequate maintenance, as well as long-term neglect and exposure to weather have caused significant structural and non-structural damage to the building. In the parts of the wall close to the ground, the moisture caused the so-called biological corrosion, which is manifested by the appearance of fungi, lichens and moss on the facade, because these organisms can live only on a wet surface. By determining the type and degree of damage to the stone blocks, the initial traces of decay, erosion and flaking were observed [6]. The church does not have stone plastic and carved structural elements, so their damage was not even considered. Only the side entrances to the church are bordered with dressed stone, and the intense effects of algae and lichens can be seen on them.

During the last reconstruction, the method of load transfer to the vaults was changed from continuous to concentrated. The load from the wooden roof structure was transferred along the top of the vault in the form of linear reactions. Arched structures are sensitive to concentrated load, so that for the same total load, up to 50% higher tensile stresses created by bending are generated on the intrados of the vault (Fig: 3) [7,8].

The characteristic of stone masonry vaults is low tensile strength due to low tensile strength of the mortar and insufficient bond between the stone and the mortar [9]. The tensile strength of the vault depends on the type and quality of the mortar with which it is built, as well as the porosity, surface roughness of the stone and the geometric relationships of the stone used for masonry. The compressive strength of masonry vaults is considerable. Although local stone crushing can theoretically occur, global failure due to pressure is unlikely, because the compressive stresses are negligible in relation to the compressive strength of the vault. The cracks in the vault were created by the action of edge tensile stresses caused by bending (Fig: 4). The cracks extend mainly through the mortar and through the joints of mortar and stone.

Fig. 4 Cracking in the barrel vault of the st. Nicholas church, (photo: P. Petronijević)

The basic step for the assessment and identification of the causes is accomplished through the examination of visible signs of damage (cracks, fissures, crushing, settlement, ...). The analysis of structural instability was undertaken, and on the basis of the collected data, the causes of damage were defined and their further propagation was predicted. Based on the five-year evaluation, a design of necessary works, interventions, construction phases, checking of temporary status during rehabilitation and necessary funds for work was made.

Analysis of cracks and the study of the causes of cracks are the basis of the diagnostic problem. In order to obtain reliable results, all relevant data related to the structure in question must be taken. Vaults made of hewn stone consist of a number of elements that function by transmitting pressure forces from one to the other and transfer the entire resulting pressure to the retaining walls. In the church of St. Nicholas the vault was made in two layers, the intrados was built with relatively regular stone, which was locally accessible, and the upper layer of the vault was made of riprap. Arched structures constructed in this way are more sensitive to changes in the regime of gravitational load transfer as well as to seismic effects. Dominant cracks in the vault can be varied.

Longitudinal cracks occur mainly as a result of differential settlement or spacing out of supports. They form on the tensioned side of the plastic joint. They become dangerous only if there are significant horizontal movements of the retaining walls. Cracks at the junction of the vault with the support indicate the process of separation of the vaulted structure and the absence of the transfer of the entire pressure force to the wall. Transverse cracks usually occur at the junction with the transverse walls or at the end of the vault. They are the consequence of inadequately constructed vault-transverse wall connections and the absence of longitudinal constraint of the vault. In modern churches with this type of structure, the crowns of the walls must be strengthened with a horizontal reinforced (RC) concrete ring (Fig. 5).

Fig. 5 Reinforcement of the masonry vault with RC shell layer (photo: P. Petronijević)

The distribution of cross-sectional forces of arched structures depends on the geometry of the support line, the conditions of support and the load constellation. Asymmetric and concentrated loads are undesirable. Vaulted structures withstand pressure stresses well, which cause oblique reactions of supports. In order to ensure the desired behavior of the vault, the compression force must be as close as possible to the center of gravity of the cross section. The bending moment caused by the eccentricity of the normal force is considered a parasitic influence in arched structures [10]. The ideal shape of the support line is given by the inverted catenary equation [7]. Tension must be prevented, the resulting force must remain in the middle third of the height. The failure of the arches is caused by the occurrence of several plastic joints, which causes the system to become a mechanism.

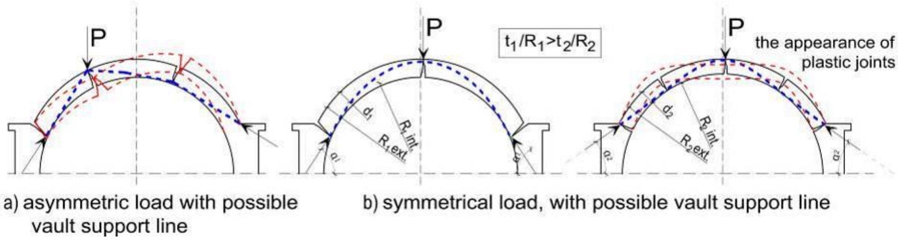

Fig. 6 Potential fracture mechanisms of barrel vault and arched structures [3]

The present damage to the vault is only partly a consequence of the concentration of load that occurred during the inadequate works in the last stage of the rehabilitation works, on the roof of the church. The bracings failure had the greatest effect on the onset and propagation of cracks in the vault. Bracings have the role of receiving the horizontal component of the oblique reactions of the arches. Thus, the longitudinal walls are entrusted exclusively with the vertical component of the reaction of the vaults, i.e. gravitational load.

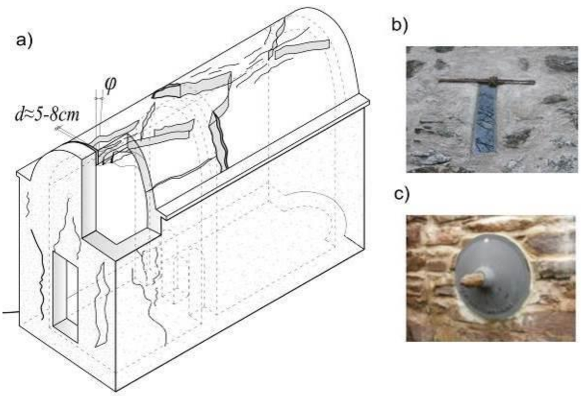

Fig. 7 a) mapping of cracks, b) influence of wall spacing and different settlement of supports on change of stress state and mechanism of barrel vault fracture [3]

The drop in the tensile force in the braces ensued due to loosening of the assembly joints, creep of the material, corrosion as well as inadequate anchoring on the outside of the longitudinal walls. Anchoring was realized with two steel members (see Fig. 7-b) in inadequate places, one brace even passing through the window. Anchoring did not include base plates so there is no possibility of subsequent force correction by increasing the tension. Arched structures are extremely sensitive to the spacing out of the supports. Braces failure and the walls spacing out at the height of the cornice by only 0.1% of the vault the span, increases the tangential tensile stress in the apex and the arch support several tens of times. This exceeds the tensile strength of the mortar multiple times, cracks and fissures occur and the supporting line of the vault is deformed depending on the number of newly formed plastic joints (see Fig. 8-a).

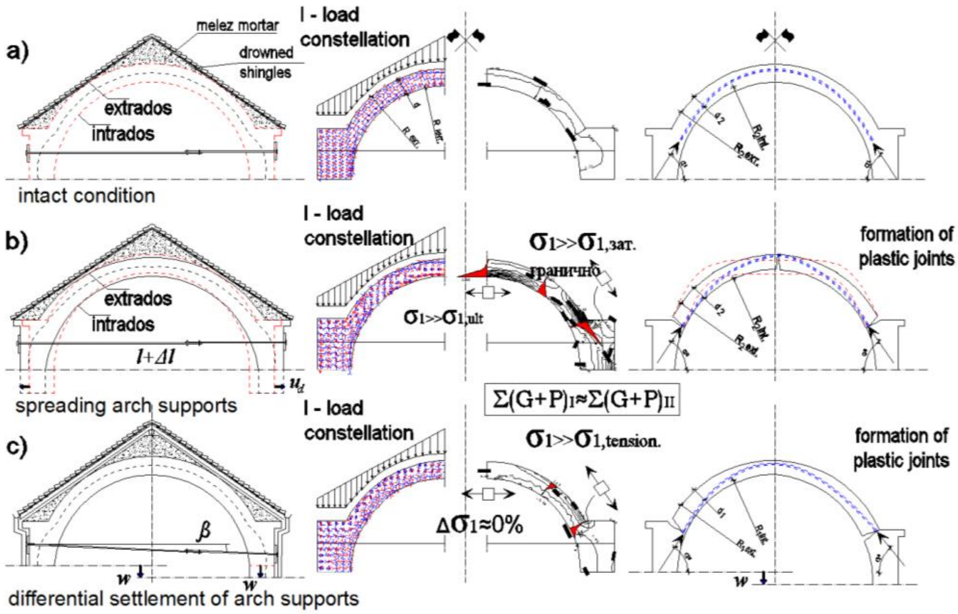

Fig. 8 The influence of wall spacing and different settlement of supports on the change of stress state and the mechanism of vault fracture [3]

The braces failure caused a widespread network of cracks in the vault, which creates a potential danger of their partial collapse. Vertical differential settlement of retaining walls has a significantly smaller impact on the change of stress state in the vault. The observed network of cracks does not indicate this phenomenon. The asymmetrical arrangement of cracks and significant areas of flaked mortar on the intrados of the nave vault occurred as a consequence of the roof leaking over a period of time.

Fig. 9 characteristic cracks between the vault and the transverse walls (photo. P.P.)

Since the walls are the supports of the vaults, their condition is vital for the stability of the structure. The depth to span ratio of the vaults is low so that the load from the roof and the own weight of the vaults are dominantly transmitted by normal forces inside the vault. Inefficient transverse bracing using metal members resulted in considerable spacing out of the support points of the vaults. This caused a flexural deformation that the structure of the vault built of stone is not able to receive. The spacing of the vaults caused the greatest consequences at the junction of the vaults with the transverse walls (Fig. 9).

Cracks in the longitudinal walls are present in places (Fig. 10), but they are significantly smaller in width than the cracks in the transverse walls. The width of the cracks registered in the longitudinal walls is up to 2 mm and is probably a consequence of the settlement of the foundations and climatic influences. In general, the causes of uneven settlement can be divided into the original ones, which stem from the inadequate dimensions of the foundations and the subsequent ones, which arose during the service of the building and are the result of water seeping into the foundations. The unevenness of the foundation soil below the building is excluded in this case. The variable depth of the foundations also had a negative effect on uneven settlements, because for the same width of the foundation strip, if the pressure is transferred to the deeper layers of the soil, the settlements are smaller. Extreme climatic conditions caused material fatigue and led to the onset of cracks of smaller or larger width. The highest concentration of cracks is at the junction of the walls in the corners of the narthex and is a consequence of the spaciong out of the arches and separation from the transverse walls (see Fig. 9).

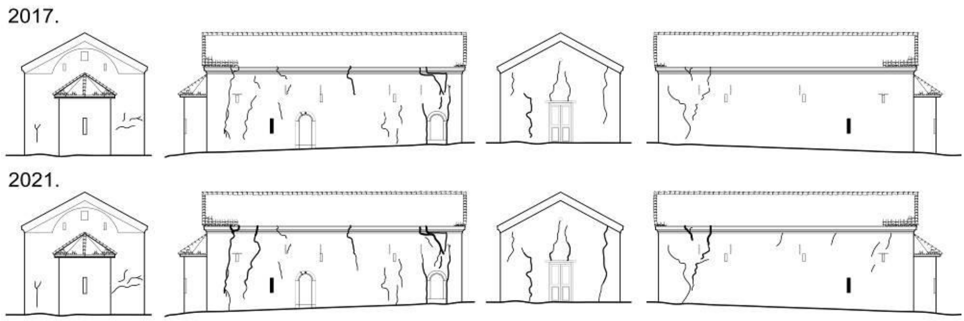

Fig. 10 Mapping cracks in the walls, condition from 2017-2021 (drawing: P. Petronijević)

Only the width of cracks larger than 5 mm indicates a significantly disrupted load-bearing structure and function of the walls and endangered stability of the vaults [6]. Although the current width of the cracks in the walls is not large, their arrangement and propagation in the last five years indicates the development of unfavorable processes. The existing map of cracks provides favorable preconditions for the occurrence of characteristic fracture mechanisms of walls during seismic actions. (Fig. 11). The possible unfavorable development of fracture mechanisms is significantly influenced by the absence of ring beams in the cornice and along the height of the wall.

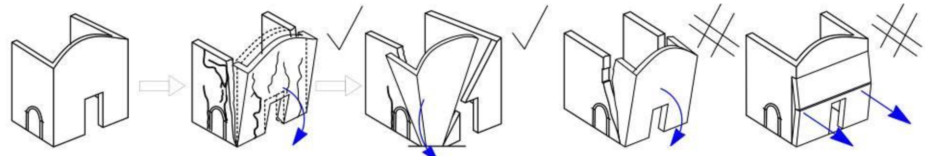

Fig. 11 Potential fracture mechanisms predisposed to the existing crack system

Horizontal movement of the cornice of the walls can be caused by: excessive horizontal component of the vault thrust force, rotational failure of the foundation structure, loss of tensile force in the braces, reduction of the vertical load. With the reduction of the horizontal load-bearing capacity of the wall and the spacing of the vault, a system of characteristic cracks appears within the deformed zone of the vault. Its manifestation is the separation of the vault from the walls, the occurrence of longitudinal cracks, and an increase in the deflection of the middle of the vault.

6. The Church Rehabilitation

Renovation of the supporting structure of the church of St. Nicholas was realized in 2021 and included the strengthening of the foundations of all external walls and the construction of a drainage system. The opening of the probing pits established a deviation in the depth of the foundation of the church walls in relation to the existing technical documentation of the ZZSK Nis from 1989 [1]. The depth of the foundation was on average 70 cm, and in relation to the available documentation, it is 50 cm smaller. The smaller depth of the foundation caused a greater degree of lateral displacement of the crown of the longitudinal walls due to the rotation of the foundation [see Fig. 12]. The longitudinal walls rotated slightly as rigid bodies. The rotation of the walls is more pronounced in the part of the narthex in relation to the nave because vertical cracks were recorded on the west façade. Further analysis of crack morphology concluded that the influence of frost and the formation of ice lenses has a significant impact on wall degradation because cracks in longitudinal walls are more numerous, sequential and extend continuously from the foundation to the crown of the wall. For that reason, and also because of the extremely difficult climatic conditions, it was necessary to increase the depth of the foundation below the freezing zone. The underpinning was realized in segments, the depth of the foundation was increased by an additional 50 cm, and an RC ring was formed on the outside of the walls. It has the role of receiving the tensile forces in the foundation zone of the walls. Reconstruction of the foundation in combination with the strengthening of the crown of the walls aims to increase the overall load-bearing capacity of the walls, which would provide secure support to the vault.

The excavated trench for the needs of strengthening the foundation was used to place a drainage ring around the entire building. Drainage was constructed using a typical system with perforated PVC pipes, covered with coarse-grained aggregate and lined with geotextile fabric. In parallel with the percolating water drainage channel, a system of surface drainage also capturing the water from the downpipes evacuating water from the church roof was also constructed.

Since moisture was the greatest danger to the quality and durability of stone and masonry structures, many causes of degradation of the church of St. Nicholas in Crna Trava were eliminated by waterproofing the foundations (see Fig. 13) and keeping the structure completely dry. Due to the effect of frost, the most common types of degradation of walls in the zone of capillary rise of water occurred: deterioration of the original mortar, deterioration of the repair mortar, disintegration of the foundation part of the wall and opening of caverns. Biodegradation was also not negligible. The plinth part of the walls turned green over time due to the moss and lichen, and over time grass also took root, further degrading the structure. The zone of plant penetration in the initial phase of works was cleaned to a height of 40 cm, with complete removal of biodegraded mortar which was replaced with repair mortar. For the restoration of the plinth wall, a mortar with a low salt content was used, which in terms of mechanical, chemical and structural properties approximately corresponds to the original material.

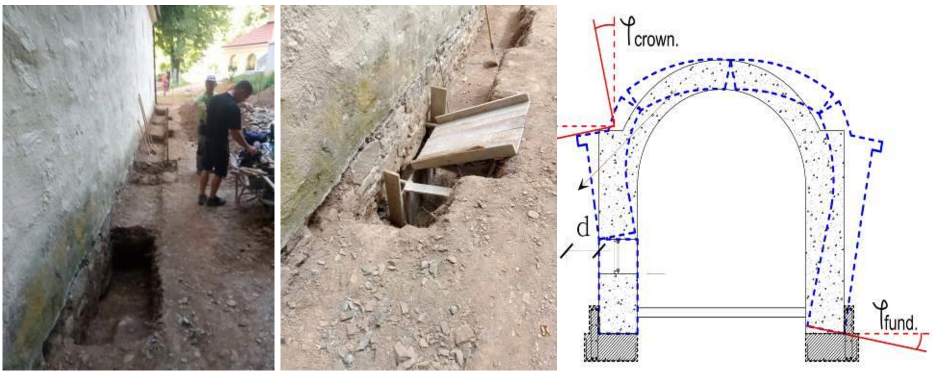

Fig. 12 Foundation underpinning

The potential of treating the walls with penetrating agents was limited due to the variety of applied stone and large deviations in porosity. Surface treatment of walls with penetrating agents without their penetration into the depth of the wall section can have negative effects. Water would continue to penetrate under the treated layers, but its evaporation would be prevented by the coating, so it can evaporate only under a certain layer, where soluble salts crystallize and cause degradation of the wall structure. Also, different humidity and thermodynamic properties would further accelerate the degradation of the wall. For that reason, low-viscosity polymer solutions applied with a pipe system, preferably under pressure, should be used for impregnation and conservation of foundation and plinth parts of walls. This type of protection is more effective with more porous stone walls. This improves many properties of the wall: it reduced capillary water absorption and improved frost resistance, while the quality parameters: water vapor diffusion coefficient, water vapor permeability, diffusion resistance coefficient did not change or changed within satisfactory limits.

The cause of the decay of the plaster is the absorption of moisture that is present on the facades during precipitation and in the vaults due to the leakage of the roof covering. The possibility of preventing the penetration of water into the walls by sealing surfaces with different types of synthetic materials should be taken with a reserve if the passage of water in the gaseous phase is prevented. Coating the wall prevents the penetration of water into the interior of the material, but prevents the water vapor diffusion flow because the material does not have sufficient vapor permeability. By choosing the right material, this phenomenon can be prevented. Silicate-based protective agents are most commonly used for this purpose. With these agents, the basic inorganic structure binds well to the inorganic substrate of the mortar and thus provides good permeability to gases. For efficient impregnation based on silicone agents, continuous application in several layers is necessary. With the correct choice of silicone agents and their adequate application, it is possible to slow down the process of deterioration of plaster and walls.

Fig. 13 a) reconstruction of the plinth wall, b) hydro-isolation, c) drainage (Photo P.P.)

The next step of the renovation includes the comprehensive repair of the vaults and the structural grouting of the stone walls. The way in which arched structures behave under static load is conditioned by several types of reinforcement. By changing the geometric shape (thickening of the arch), which affects the shape of the support line of the segments between the plastic joints. The goal is for the geometric shape to make the structure be predominantly stressed by compression, while the radial deformation and tension are limited. By increasing the thickness of the vault, the integrity is restored by removing the two plastic joints. The support line in the case of an arch with developed plastic joints touches the intrados and / or extrados, while with reinforcement it moves back within the geometry of the arch. If the vault shows visible deformations and the beginning of the development of the fracture mechanism, as in the case of the church of St. Nicholas, strengthening and rehabilitation require other types of intervention as well.

The method of strengthening the vault by increasing the thickness using the concrete saddle, despite its high efficiency, is used cautiously due to incompatibility of mechanical characteristics of concrete and that of the stone or brick vault, asymmetry of cross section and relatively destructiveness of the method [11]. The modulus of elasticity of masonry stone varies a lot and depends on the quality of the stone and the applied mortar, the type of bond and layering of the wall, the degree of stone dressing, etc. The efficiency of the solution largely depends on the degree of bond, so it is necessary to prepare the contact surface and apply anchors that resist the shear between the brick and the RC vault (see Fig. 14). Intrados shotcreting gives partial results in strengthening the vaults due to the small thickness of the additional layer. The method was popular in the 70s and 80s, but in this case it is not applicable so that the frescoes would be preserved.

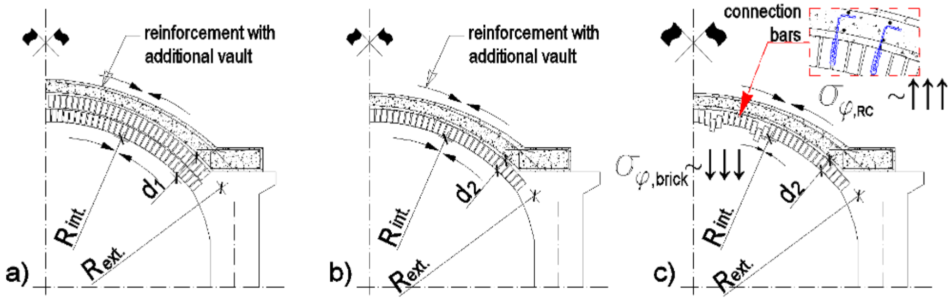

Fig. 14 Reinforcement with additional vault

Preservation of frescoes also prevents the application of composite polymers (fiber-reinforced polymer - FRP) on the intrados of vaults. In recent years, the application of FRP has been very common in the rehabilitation and strengthening of masonry and arch structures [8]. FRP reinforcement is very effective because it increases the tensile strength at the places of plastic joints. The method of reinforcement with steel arches is suitable for arches made of large stone blocks. An example of the successful strengthening of the vault with a series of steel arches is the construction of the Temple of Jupiter in Split. The absence of a massive cornice at the level of the arch support limits the application of this method in the case of St. Nicholas church. For that reason, the solution of strengthening the extrados of the vault with an additional layer of reinforced concrete with the addition of a more massive concrete ring beam is more favorable. This efficient solution has been applied many times in practice and is a common procedure for making vaults during the construction of new buildings (see Fig. 15). In this way, the structural response of the vault (load-strain) is significantly improved. Since it is not possible to influence the geometry of the vault during repairs, the stress state can be improved by changing the function of the added vault cross-section. Subsequent arch constraining is difficult to perform, so the support connection is considered hinged or elastically constrained. For most remediation procedures, a constant cross-section of the vault reinforcement is advantageous or it changes so that a larger mass is concentrated along the supports (the thicker the layer of concrete along the supporting walls) At the locations of cracks on the intrados, it is possible to use Polymer-reinforced fibers as these materials give higher tensile strength at the expense of a slight increase in weight [12]. For this purpose, Steel Reinforced Grout can also be used, which is also an effective solution for strengthening vaults in order to increase their load-bearing capacity and seismic resistance [13-15].

Fig. 15 a) Reinforcement of the vault extrados with steel arches, b) masonry vault reinforcement with additional RC vault (photo: P.P.)

7. Conclusion and Final Remarks

After the continuation of the research works on the church, which included probing the foundations and determining their depth, adequate bases were created for the preparation of design documentation for the foundation underpinning and the drainage system around the church. Structural rehabilitation of foundations and walls was realized, with the development of a drainage system for collecting and draining percolated and atmospheric water. In addition, the necessary works on the repair of the roof structure, the roof covering and the flashing were performed. In the next phase, works are planned on strengthening the vaults of the ceiling: by grouting, using repair mortars with the possible application of composite materials on the inside under the mortar, because the outer part of the church is made of stone. By grouting and joining, cracks in the vaults must be repaired and thus the harmful effects they cause on the material and structure must be eliminated. It is necessary to strengthen the entire vault by making an RC saddle on the extrados. It is necessary to repair the braces on the basic construction, do anti-corrosion protection and tighten them. It is desirable to change the anchor braces and replace the existing wedges with steel base plates. Cracks in arches and walls that extend along the entire thickness of the walls should be injected. Larger cracks in the vault are filled with repair polymer mortar. The repair of cracks in the transverse walls and vaults should be based on the installation of additional steel braces inside the nave and anchor them using the plates on the outside of the wall. The bracing of the longitudinal walls should be achieved with RC cerclage in the crown of the walls, which is also the completion of the reinforcement of the vault with RC saddle. These works should be carried out while preserving the visual integrity of the building. Conservation and restoration works are necessary on the interior fresco paintings. Subsequent layers of mortar should be removed, cracks should be grouted, semi-bonded parts of the mortar should be fixed and the painted layer should be retouched.

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PROCENA STANJA I KONSTRUKTIVNA SANACIJA CRKVE SV. NIKOLA U CRNOJ TRAVI

U radu je analizirano stanje konstrukcije crkve posvećene Svetom Nikoli, koja se nalazi u varošici Crna Trava, na jugu Srbije. Data je arhitektonska analiza posmatranog objekta, kao i pregled dosadašnjih radova na njemu, kako istraživačkih, tako i onih sanacionih i konzervatorskih. Prikazana je detaljna analiza konstruktivnog sklopa crkve. Izvršena je analiza i klasifikacija uočenih oštećenja, prikazani su radovi na rehabilitaciji objekta, a dat je i predlog daljih sanacionih mera sa ciljem sprečavanja daljeg propadanja objekta.

Ključne reči: *svod, oštećenja, degradacija, crkva, rehabilitacija*

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Original Scientific Paper

DESIGN OF ATYPICAL FACADE ARCHITECTURAL ELEMENTS AS NOISE REDUCTION BARRIERS - CASE STUDY

UDC 699.844

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Abstract. *The presented work is the result of affirmation of synergistic work of experts dealing with architectural and acoustic design with the aim and purpose of finding an adequate solution for optimal correction of the effect of GHG systems installed on the facade of the subject (case study) office building in Belgrade. Measurements established that the noise of the constructed GHG systems affected the residential building in the immediate vicinity. The effect of the constructed devices (refers to the installed units) of the office building in question in the case when they operate at full capacity was measuring to be about 58 dB (A). The urban zone in which the building is located (Vracar-Belgrade) belongs to the category of "office-residential area" in which the outdoor noise level permitted for the period of day is 60 dB (A), and for the night period is 50 dB (A). Taking into account the stated facts, it has been unequivocally established that GHG systems to a certain extent exceed the permitted noise levels and "endanger" the neighboring observed building. The subject of this professional-scientific research is the design of atypical facade architectural elements as a barrier reducing noise on the example of an office building in Belgrade. The architectural challenge was reflected in the fact that, in addition to designing the facade element which, at the request of the investor must not compromise the architecture of the building, therefore, should be "atypical in architectural design", it must also provide flexibility in applying different variants of acoustic barriers, which in addition to architectonic requirement must provide an adequate response to acoustic requirements. To the satisfaction of the authors, the designed barrier confirmed a successful synergy solution. The adopted architectural-acoustic configuration of the barrier proved to be effective regardless of the type of installed air conditioners, which in some way justifies the initial idea of strong causality of acoustic and architectural design, as a synergistic principle.*

Key words: *Architectural design, Noise reduction barriers, Atypical facade architectural elements, Software prediction,*

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1. INTRODUCTION

Noise is any undesirable sound that interferes with a person's rest and work. The main sources of noise in the environment are outdoor and indoor noise sources. Outdoor sources of noise are most often road, rail and air traffic, concerts, parks, construction machinery and industry, while in the indoor space noise is produced by air conditioners, transformer stations, discos, concerts. Noise, as a mixture of sounds of different properties, endangers human health in many ways, and it is also one of the biggest polluters of the environment [1], [2]. Noise pollution affects the work environment, and this problem is present not only in residential buildings, but also in schools, universities, offices and hospitals.

According to estimates by European institutions, a large number of people in Europe live in areas where the noise level exceeds the recommended values. It is estimated that 113 million people are affected by long-term traffic noise levels of at least 55 decibels (dB (A)). In most European countries, more than 50% of urban dwellers are exposed to road noise levels greater than 55 dB. The EU considers that long-term exposure to noise levels over 55 decibels is high, while the World Health Organization indicates that this has a negative impact on human health [3].

According to the Law on Protection from Noise [4], anyone who "makes noise emissions is obliged to monitor the emissions and limit its impact within legal regulations." Air conditioners can cause excessive noise levels in a room [5]. In situations where noise cannot be avoided, such as when air conditioners are installed on the facade of a building, it is necessary to perform all necessary interventions to reduce the noise level.

The subject of this scientific research is the design of atypical facade architectural elements as barriers reducing noise on a specific example.

In this paper was performed a comparison of values obtained in two ways, by experimental measurement and software. The performance of the designed barrier was estimated using 3D simulations.

2. PROBLEM DEFINITION

Sound insulation of facade structures has a great effect on conducting noise inside the building [6]. So far, several techniques have been developed based on different approaches to assess barrier effects, using numerical, experimental and empirical methods [7] - [9]. For barrier designers and manufacturers, the contribution of computer modeling makes it possible to predict sound attenuation already in the product design phase [10].

Based on the complaints of the tenants, insight into the specific problem and measurements in the field, it was concluded that the noise level generated by air conditioners placed on the facade of the office building has a disturbing effect. The relationship between the position of the office building where the air conditioners are located and the endangered residential building, as well as the appearance of the air conditioner on the facade of the business building are shown in Figure 1. Based on this, it is possible to consider the position of air conditioners which are a source of noise in respect to adjacent buildings.

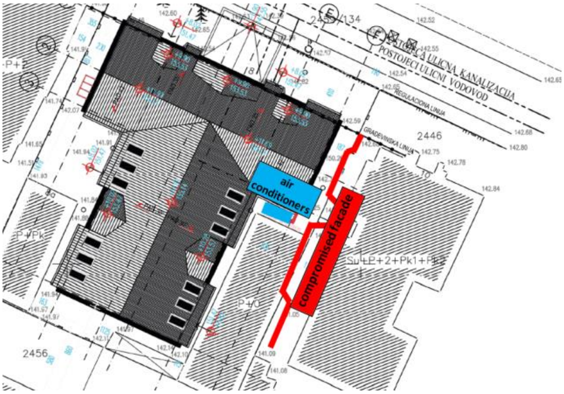

Fig. 1 General plan with the position of the office building where the air conditioners are located and affected endangered facades of the residential building (left) and a photo of the courtyard facade of the office building (right)

After checking the noise level of air conditioners by measuring the noise level at the location of the facility, the criteria for the permissible noise level of the observed air conditioners that they create in the environment were determined, the achieved noise level reduction was checked by software modeling, and the details for realization of the barrier were designed.

Permitted values of noise levels in the urban environment are determined by the document "Regulation on noise indicators, limit values, methods for assessing noise indicators, disturbing and harmful effects of noise in the environment" (Official Gazette of RS No. 75/10). The Regulation defines the limit values of noise indicators according to acoustic zones. The zones are determined by the predominant content of the buildings located in them. The methodology for determining acoustic zones in settlements is defined in the document "Rulebook on methodology for determining acoustic zones" (Official Gazette of RS, No. 72/2010). Definitions of acoustic zones and values of the maximum allowed value of noise levels in the external environment are shown in Table 1. The values from Table 1 refer to the levels measured at the property boundary, which in the urban environment represents the facade of the building.

Table 1 Limit values of outdoor noise indicators

Zone	Area Use	Noise level in dB (A)	
		Day and evening	night
1.	Areas for rest and recreation, hospital zones and recuperation areas, cultural-historical locations, large parks	50	40
2.	Tourist areas, camps and school zones	50	45
3.	Purely housing areas	55	45
4.	Office-residential areas, commercial-residential areas and children playgrounds	60	50
5.	City center, craftsmen, trading, administrative zone with apartments along highways and major and city roads	65	55
6.	Industrial, storage and service areas and transport terminals without residential buildings	At the border of this zone, the noise must not exceed the limit values in the zone it borders	

The zone of the city in which the analyzed facility is located belongs to the category "business-residential areas", which means that the prescribed values of noise levels in the outdoor environment for day and evening are up to 60 dB (A), while for night those values are up to 50 dB). The same Regulation defines the limit values of noise indicators indoors. The prescribed values in the living rooms of apartments (bedrooms and living rooms) with closed windows are up to 35 dB (A) for day and evening, while up to 30 dB (A) for the night. Limit values for noise levels indoors do not depend on the zone in which the residential building is located.

To assess the risk of noise from sound sources located in the external environment, the criterion for outdoor noise according to the appropriate zone of the city must be used. Noise in the premises of buildings cannot be a criterion for assessing the threat from external sources because it depends on variable factors such as the quality of windows in the premises and noise sources located inside the building.

2.1. Analysis of the existing noise state -

The analysis of the current state of ambient noise at the location was performed by a measurement conducted on June 21st, 2021. The measurement was performed in two modes of operation of the noise source:

- when all air conditioners are turned off to define the ambient noise level at the location,
- with all outdoor units of the device operating at their maximum power.

The purpose of this measurement is to obtain data for calibration of the software model and algorithm with which the calculation of noise levels on the facade of the residential building was performed.

The measured values of the noise level in the circumstances when all air conditioners are operating at the maximum power show that the noise level exceeds the allowed value for the night period which is 50 dB (A). For example, the measured value of the equivalent noise level at one measuring point was 58.5 dB (A). Subjectively (by listening), the sound of the outdoor units of the air conditioner is clearly recognized as dominant in the sound that is heard on the location.

Measurement of noise levels in circumstances when all air conditioners are switched off shows that the noise level at the used measuring points is approximately in the range of 46-49 dB (A). Subjectively (by listening), it was estimated that the existing ambient noise predominantly originates from the air conditioners in the residential building, where there are four outdoor units, one of which is of slightly higher power.

A detailed calculation of the noise level in the outdoor environment, which refers to the condition without a built-in protective barrier, was performed for two variants of outdoor units. One relates to devices that are installed on the facility, and the other to devices from another manufacturer that are provided by the designed solution.

Five LG devices are installed at the office building, in the following order: ARUN 120LSS0, ARUN 100LSS0, ARUN 80LSS0, ARUN 60LSS0, ARUN 50LSS0. The design of the building comprised DAIKIN devices, respectively: RXYSQ12TY1, RXYSQ10TY1 ("Ground floor" systems), RXYSQ8TY1 ("Attic 1" systems), RXYSQ6T8Y ("Basement" systems), RXYSQ5T8Y.

The calculation of the noise level on the facade of the neighboring residential building in its current state with built-in devices manufactured by LG, even when all devices are working at maximum power, shows values around 55 dB (A), and in some zones exceeds 60 dB (A).

The calculation of the noise level with the designed devices manufactured by DAIKIN shows that the noise level on the most affected parts of the facade would be on average lower by 1-1.5 dB compared to the built-in solution with LG devices. In both cases, considering the constructed and designed solutions, when working at maximum power, the noise level on the facade of a residential building exceeds the values prescribed for the night period. From the aspect of affecting a residential building with noise, there is practically no difference between them because 1-1.5 dB is within the limits of measurement uncertainty when measuring noise levels.

The measurement results showed that the level of that noise exceeds the permitted value.

3. Design as an Architectural and Acoustic Challenge

Due to the specific configuration of buildings and the position of outdoor units, calculations have shown that it is necessary to form a barrier that maximally shields the units. The barrier on the inside must be lined with a highly absorbent material. The efficiency of a noise barrier largely depends on its geometry [11]. Figure 2 shows the appearance of the southern facade of the office building with a barrier, while Figure 3, Figure 4 show the details of the construction of the designed protective barrier solution to reduce the effects on the residential building

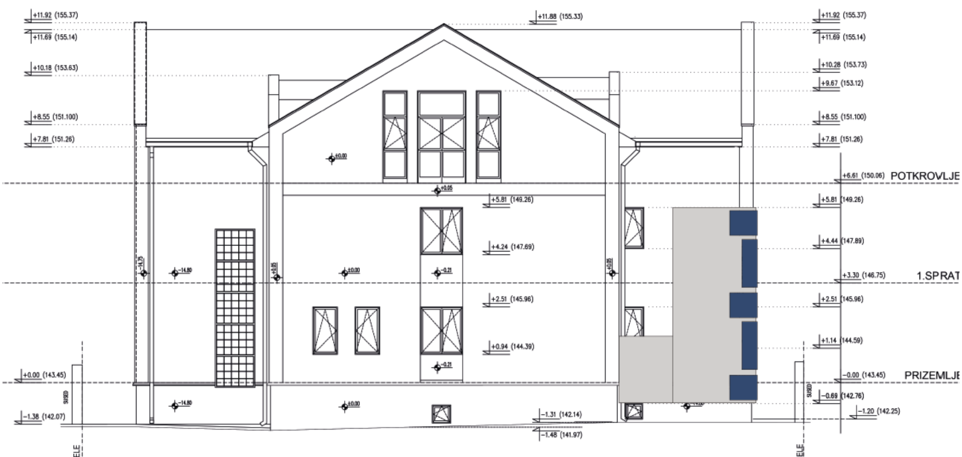

Fig. 2 Appearance of the southern facade of the office building with the installed barrier

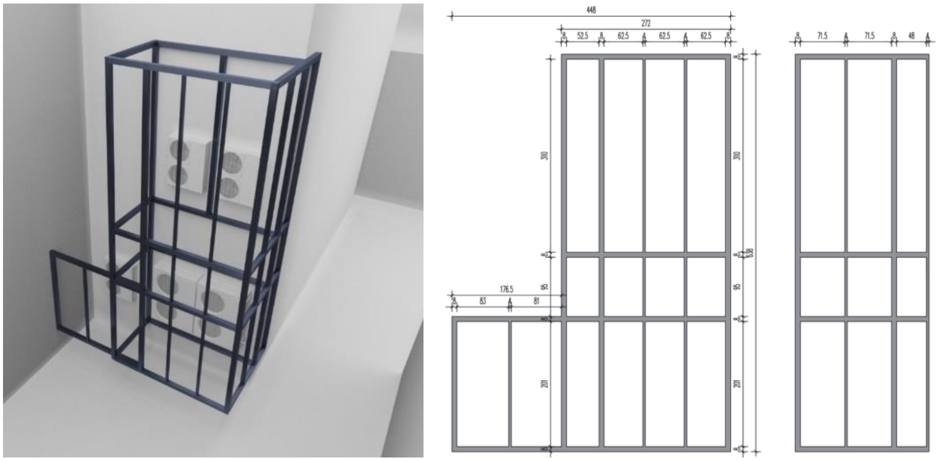

Fig. 3 Appearance of the steel structure of the designed barrier (left) and dimensions of the steel structure (right)

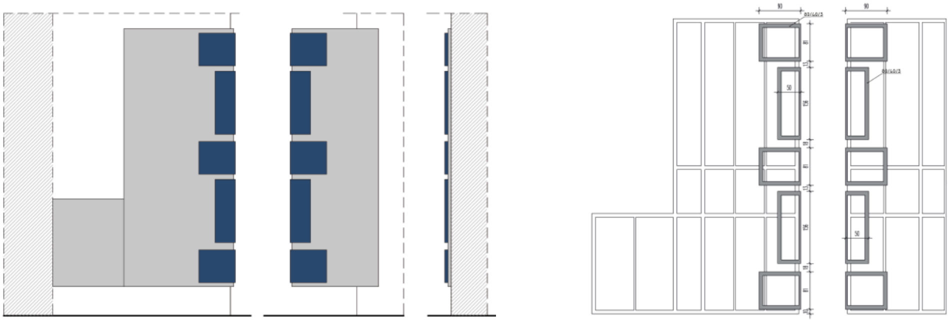

Fig. 4 Appearance and dimensions of facade barrier structures

For the designed barrier, noise level calculations were performed on the facade of the adjacent building for the case when the outdoor units operate at maximum power. The calculation results show that the noise levels on the facade of the neighboring building with a built-in barrier do not exceed the values of 50 dB (A). This satisfies the criterion of noise in the outdoor environment for the residential-business zone for both day and night mode. The same calculation was made for the case when DAIKIN air conditioners, which are planned by the design, would be installed. From the results presented in Annex 5, it can be seen that the differences in the values of noise levels are up to 1.5 dB, as in the case without a protective barrier. This difference is within the measurement uncertainty that is inherent in the procedure of measuring sound levels.

4. MEASUREMENTS AS A REFERENCE POINT

This section presents the results of the control measurement of noise of outdoor units of air conditioners in the current state. Figure 5 shows the measuring points where control measurements were performed. The measurement was performed at two measuring points positioned on the upper edge of the wall that separates the plot of the office building from the adjacent plot of the endangered residential building. The measurement sites and the obtained results are shown in Figures 5 and Figure 6.

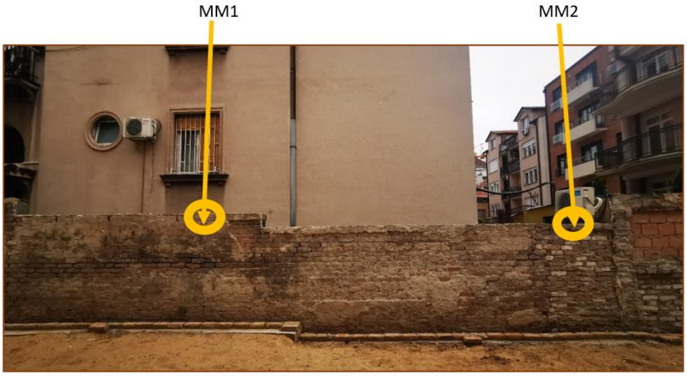

Fig. 5 Photograph of the wall separating the plot of the business building and the plot of the neighboring residential building; the positions of the measuring locations places are marked (view from the side of the office building)

Figure 6 shows the measured 1/3 octave spectra of the equivalent noise level at the measuring positions MM1 and MM2 for the case when all air conditioners are turned off and when they are all on and working at full capacity. The graph also shows the equivalent A weighted noise levels for both measuring positions with and without air conditioning on.

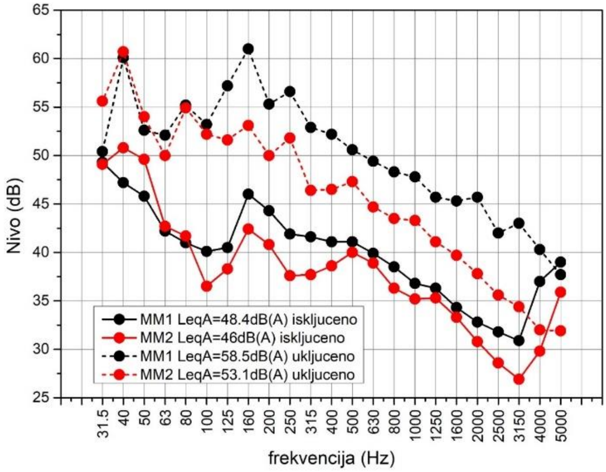

Fig. 6 Results of noise level measurements at two measuring points (MM1 and MM2) when all air conditioners are switched off, and when all are switched on and working at full capacity.

5. Simulations

The results of the calculation of the noise condition on the entire facade of the residential building are shown in the figures. Figure 7 (left) shows the result for the case such as the current state of the building, i.e. with built-in devices manufactured by LG, and Figure 7 (right) for the case of devices manufactured by DAIKIN that are planned by the design. The images show the calculated values of the noise level in the zone directly in front of the facade in a certain grid. All values are in dB (A).

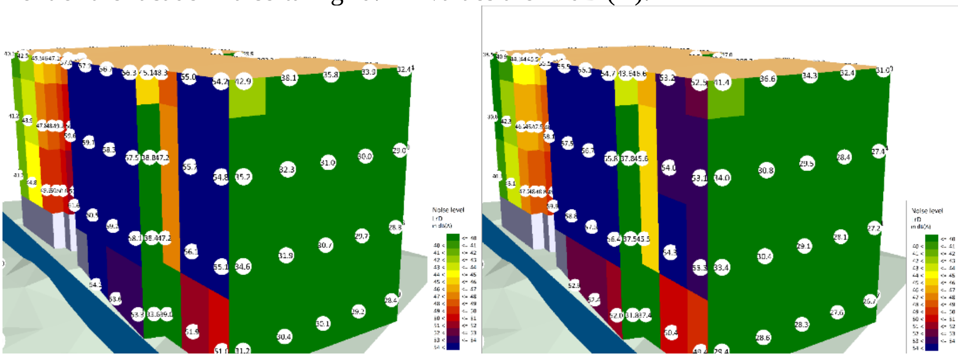

Fig. 7 The result of the calculation of the equivalent noise level on the facade of the neighboring residential building in the case of LG (left) and DAIKIN (right) outdoor air conditioning units, during their operation at maximum capacity; all values are in dB (A).

6. Calculation of Noise Condition on the Façade of a Residential Building with a Protective Barrier

The results of the calculation of the noise condition on the entire facade of a residential building with a designed protective barrier are shown in the figures. Figure 8 (left) shows the result for the case of the current state of the building, i.e. with built-in devices manufactured by LG, while Figure 8 (right) shows the result for the case of devices manufactured by DAIKIN that are planned by the design. The images show the calculated values of the noise level in the zone directly in front of the facade in a certain grid. All values are in dB (A).

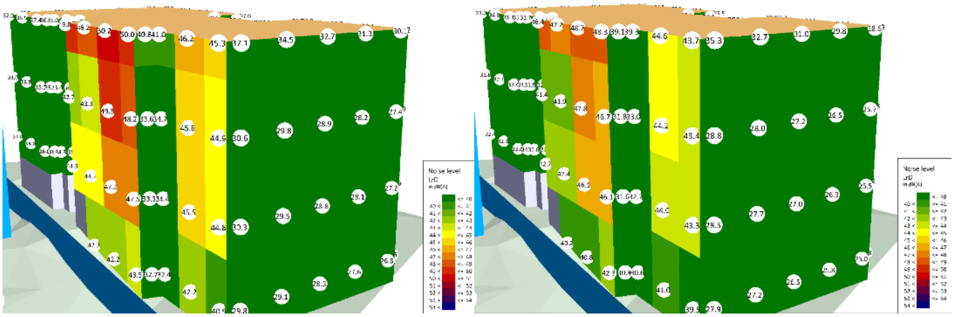

Fig. 8 Calculated values of equivalent noise level on the facade of the nearest building with built-in LG (left) and DAIKIN (right) units and a designed barrier

7. Conclusions

Designing atypical façade architectural elements as barriers to noise, in addition to being a great challenge for architects, also contributes to the improved acoustic comfort of people. In this paper, a comparison of values obtained in two ways, by experimental measurement and software was performed. The performance of the designed barrier was estimated using 3D simulations. During the design, different variants of barriers were considered, which, in addition to architectural principles, must also meet acoustic requirements. The calculation shows that the adopted barrier configuration is effective regardless of the type of air conditioner installed, given the small difference in the maximum noise levels they produce.

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PROJEKTOVANJE ATIPIČNIH FASADNIH ARHITEKTONSKIH ELEMENATA KAO BARIJERA ZA SMANJENJE BUKE - STUDIJA SLUČAJA

Prikazani rad je rezultat afirmacije sinergijskog delanja stručnjaka koji se bave arhitekatonskim i akustičkim dizajnom sa ciljem i u svrhu pronalaženja adekvatnog rešenja za optimalnu korekcije uticaja GHG sistema postavljenih na fasadi predmetnog (studija slučaja) poslovnog objekta u Beogradu. Merenjima je ustanovljeno da su izvedeni GHG sistemi ugrožavali bukom stambeni objekat u neposrednoj blizini. Uuticaj izvedenih uređaja (odnosi se na ugrađene jedinice) predmetne *poslovne zgrade u slučaju kada rade punim kapacitetom merenjem je utvrđen na vrednost od oko 58 dB(A). Urbana zona u kojoj se nalazi objekat (Vračar-Beograd) spada u kategoriju „poslovno-stambenog područja" u kojoj su dozvoljeni nivo buke u spoljašnjoj sredini za period dan 60 dB(A), a za period noć 50 dB(A). Uzimajući u obzir navedene činjenice nedvosmisleno je utvrđeno da GHG sistemi u određenoj meri premašuju dozvoljene nivoe buke i "ugrožavaju" susedni posmatrani objekat. Predmet ovog stručno-naučnog istraživanja predstavlja projektovanje atipičnih fasadnih arhitektonskih elementa kao barijera za smanjenje buke na primeru poslovnog objekta u Beogradu. Arhitektonski izazov ogledao se u tome da se, pored osmišljavanja fasadnog elementa koji, na zahtev investitora ne sme narušiti arhitekturu objekta, dakle, treba biti "atipičan po arhitektonskom dizajnu", mora pružiti i fleksibilnost apliciranja različitih varijanti akustičkih barijera koje pored arhitektonskih zahteve moraju dati adekvatan odgovor i na akustičke zahteve. Na zadovoljstvo autora dizajnirana barijera je potvrdila uspešno sinergijsko rešenje. Usvojena arhitektonsko-akustička konfiguracija barijere pokazala se efikasnom nezavisno od tipa instalisanog klima uređaja, što u neku ruku opravdava inicijalnu ideju o jakoj kauzalnosti akustičkog i arhitektonskog dizajna, kao sinergijskog principa.*

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Original scientific paper

A NATURAL APPROACH TO RIVER ENGINEERING PRACTICE. A CASE STUDY OF THE LJILJANSKA RIVER

UDC 626/627
502.171:546.212

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Abstract. *In the past 30 years the efforts to protect river beds and banks have increased significantly. The selection and design of proper structural solution means finding a solution in accordance with construction principles, river geomorphology, avoiding channel aggradation, bed scour, bank erosion, resulting structure failure and significant harm to the stream and nearby property. On the other hand, the structure should be environmentally-friendly. Hydraulic structures generally have a strong impact on the environment, so providing "the right solution" presents a real challenge to engineers.*

Key words: *hydraulic structures, environmental impact, river training*

1. INTRODUCTION

In the long history of mankind, the global balance between nature and human activities was sustained until the twentieth century when stunning technological progress ćcaused very serious environmental problems [1]. Environmental awareness has become one of the most important issues nowadays.

In the past 30 years the efforts to protect river beds and banks have increased significantly. The selection and design of proper structures means finding a solution in accordance with construction principles, river geomorphology, avoiding channel aggradation, bed scour, bank erosion, resulting structure failure and significant harm to the stream and nearby property [2]. On the other hand, the structure should be environmentally-friendly. Hydraulic structures generally have a strong impact on the environment, so providing "the right solution" presents a real challenge to engineers.

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1.1. Empirical construction principles

River training works have been practiced since ancient times. The construction principles were developed on the grounds of abundant experience during which the assessment criteria and requirements were modified almost constantly.

In addition to the applied loads, the design of a river channel takes into consideration other criteria, such as the:

- Operating period;
- Construction method;
- Flow rate and/or level regime;
- Submersed or immersed nature of the works;
- Cost of materials used;
- Compatibility in terms of environmental factors (particularly flora and fauna).

A number of principles regarding the general construction design are accepted nowadays, and according to them, the main principles in selecting river training structures are the following:

- The construction must be plastic (commonly named "elastic"), able to bear deformations of the foundation;
- The construction must be designed knowing that during the operation, inevitably, it will suffer some degradation (damage);
- The construction should not prevent the free flow of water, ice or other floating objects, particularly during flooding;
- The construction should be properly fixed both upstream and downstream to avoid deteriorations under construction caused by erosion;
- The construction should primarily be aimed at the protection of the environment and ecosystems (maintaining the habitats and water quality).

In order to ensure the restoration of the dynamic ecosystem in the area affected by the works, the design should provide possibilities for plant and animal colonization. The design may be endorsed if it provides ways and elements that facilitate the restoration of ecosystems. Considering their highly diverse nature, establishing a number of work categories from several perspectives is required, which will ensure coverage of the field and highlight its inseparable link with the environment, without claiming the complete classification.

1.2. River geomorphology – general principles

The most important natural functions of rivers and their adjacent riparian areas are the following [3]:

- a fish habitat, offering optimum breeding conditions;
- a habitat for birds, mammals, amphibians, reptiles and very diverse invertebrates;
- water and sediment retention;
- water self-cleaning by storing and recycling the nutrients and by transforming organic and non-organic pollutants;
- biodiversity – trees in floodplains are very fertile;
- its socio-economic function: the water source, waterway, exploitation of construction materials (sand and gravel), tourism, recreation and education.

The development of geophysics and ecology (especially aquatic habitats) of rivers depends almost exclusively on the dynamics (hydraulics and hydrology) and morphology of the river flow. Under natural conditions, the river flow forms a relatively stable connection between the variables that characterize the river flow.

The independent or control variables are the:

- river flow;
- sediment transport;
- hydraulic gradient;
- riverbed and bank sediment characteristics;
- riparian vegetation.

The dependent or response variables (degrees of freedom) are:

- the width of the river;
- average water depth;
- maximum water depth;
- river channel slope;
- the velocity of a river;
- spatial energy dissipation of the river flow;
- river meandering;
- mean sediment size;
- the percentage of fine-grained sediment;
- the wavelength.

In a river stream flow that is in dynamic equilibrium, the dependent variables constantly change and adjust their values. Following strong anthropogenic changes (pressures), the river tends to return to its initial parameters, and consistent natural conditions, but only if the intervention works are properly designed and performed. The structures unable adjust during the dynamic rebalance process will modify the riverbed, distorting and endangering the ecological balance of the river on much wider river sectors than the working area [4].

1.3. Environmental impacts of the river training works

The planet's human life system is an interactive force, composed of the activities of people and their institutions, ecologically dependent, which irreversibly affect the environment. Under natural conditions, the process composed of the "disturbance (ecological stress) – impact (response) – natural recovery" is a process that requires time, but will, likely, be a successful one. However, the restoration of the riverbed after morphological modification is possible; but, if the nature of the planned works, incorporated materials and location of the structure are inadequate, restoration of the ecosystem is unlikely. The impacts of river training structures are numerous and complex and are summarized in Figure 1 [4].

Reducing the number of morphological forms of the riverbed (at great depth in concaves) and reducing the instability of the riverbed shape, cause a reduction in the available habitats of endemic species and fish populations. Rivers and their corridors form a complex ecosystem that includes their inundation, flora, fauna and river flows. These ecosystems depend on river flow regimes in which flow, sediment transport, water temperature and other variables have a clearly defined role. If these variables are changed, in comparison to natural state values, the balance is disturbed. For this reason, river engineering structures should be directed toward maintaining the global dynamic equilibrium of the river flow over time and space.

The construction of embankments on long sectors of the river flow not only leads to a decrease in the biodiversity of the aquatic environment, but also to an increase in maximal flow values. The new concept of river management, "more space for the river", implies harmonization of social and economic requirements, water supply, flood protection as well as others, within the environmental requirements. To this end, the continuity of the river and its connection with the flooded area should be ensured, so that habitats (riparian areas) necessary for the preservation of aquatic flora and fauna, flood mitigation and nutrient retention will be formed. By creating connections with flooded areas, new areas for flood mitigation and nature are created. That is where novel ecosystems will be developed to provide optimal conditions for aquatic flora and fauna, as well as for recreation and tourism [4].

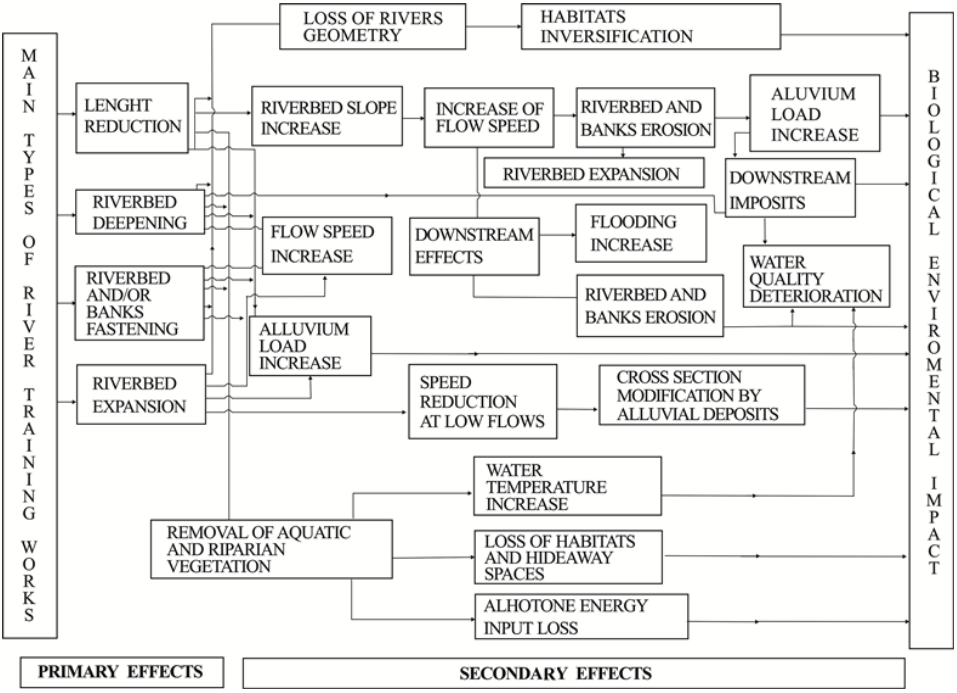

Fig. 1 Environmental impact of the river training works

It must be emphasized that there is also an environmental impact generated by the construction site. This type of impact is, usually, persistent and it covers a much larger area than the working area, experienced at high distances from the construction site.

In some cases, the impact, generated during the works execution period, is very strong and usually additionally pollutes the environment (turbidity, oils and fuels from the machineries, remains of construction materials, etc.). Therefore, in the case of river training works that cover a larger area or in which works on excavation and backfilling of riverbeds are performed, it is necessary to have a technological project, which would specify all the important measures that provide a minimum and acceptable environmental impact (finding and arranging landfills, accesses, waste disposal, conditions for control and maintenance of machines, etc., masonry cladding the river bank). A technological project receives the same requirements as a project design and must be approved alongside it. This project must be subjected to the same requirements as the river training works project and shall be approved along with the project.

1.4. Main types of river training works and their impact on the physical environment

The intensity of the impact of hydraulic structures on the environment depends to a certain extent on the type and nature of structures and accompanying river training works. The following scheme (Figure 2) indicates the main types of river training works, grouped according to the purpose of river training [4].

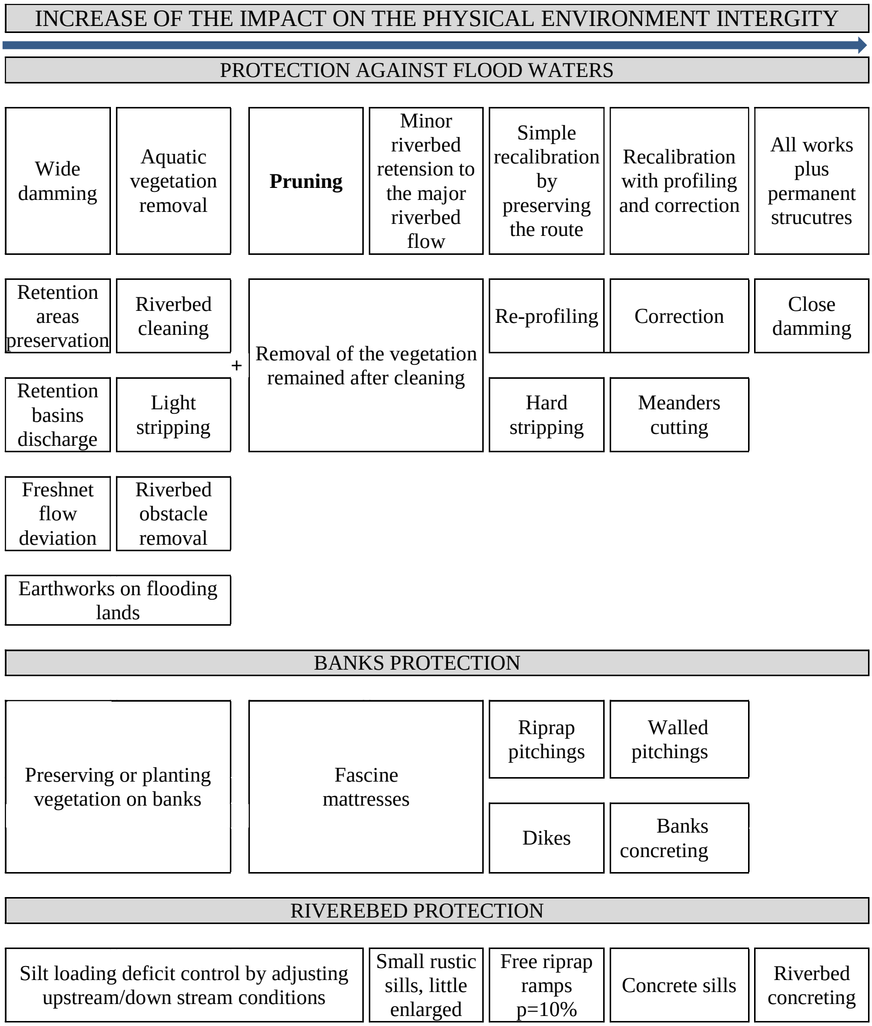

Fig. 2 Main types of river training works and their impact on the physical environment

Types of structures whose intensities are ranked starting from the highest are: all solutions that include non-adaptable structures (permanent structures), embankments, recalibration with rectification and reprofiling, meander cutting, concreting the bottom of the riverbed, concrete check-dams, masonry cladding, concrete blocks. Summarizing the types of morphological influences, it was noticed that there are three significant types of necessary data: current or long-term influence, intensity of influence and long-term stability.

The impact intensity is classified into four classes: very strong, strong, medium and weak. The very strong impact class includes the following river training work types: river course corrections, bank reshaping and reprofiling, meander curvature change, damming, derivation and deviation of the minor riverbed; the strong impact class includes: decreasing of inundation, check–dam construction and river-bank protection. The construction of embankment and meander curvature change generate, practically, irreversible environmental effects.

2. River Training Works Good Practice. A Case Study of the Ljiljanska River

The Ljiljanska river is a right tributary of river Juzna Morava. The river mouth is 2,5 km downstream from small town of Bujanovac or 2 km form the mouth of the Trnovacka river. The main stream forms the Kosaracka River and Jastrebacka or Selacka river, upstream from the village Ljiljance. The catchment area encompasses 18 km^2. The length of the stream of the Ljiljanska river is approximately 4 km. The Selacka river, as her right tributary, has a length of approximately 8 km, and the Kosaracka river, as her left tributary, has a length of 9 km. In the catchment area, the hydrographic network is a dense total area of 17,6 km^2. The approximate vegetable land cover is about 62% forest, 20% arable land and about 18% meadows and pastures [5].

Fig. 3 Willow wattles

The Ljiljanska river is one of many unregulated right torrential tributaries of the river Juzna Morava (the Bujanovacka river, Bogdanovacka river, Ljiljanska river, Zvebecka river, Krsevicka river etc.). These streams in the area of the inflow into the river Juzna Morava intersect with the Nis-Skopje railway. The constructed waterway has a lack of flow capacity and due to high water in the tributaries, upstream of the railway the coastal area was often flooded. Along the above-mentioned tributaries, a few settlements had severe problems with torrential floods. An extreme case of endangering the coastal area from the torrent of the Ljiljanska river took place in January 1996 in the section of river that passes through the village of Ljiljance, situated about 4 km from the mouth of the Ljiljanska river [5]. On this location there was specific influence of heavy and deep erosion, so the local village road – street was destroyed, several electric poles undermined and a recently constructed bridge in the village affected. A very wide river bed was formed (of over 40 m), with steep unstable river banks of average height of about 3 m. The most threatened section runs through the Ljiljance village at a length of 1400 m. The Ljiljanska river bed tends towards a permanent deepening in the middle course and collapsing banks in particular through the Ljiljance village, creating a lot of damage [5].

Fig. 4 Cascades

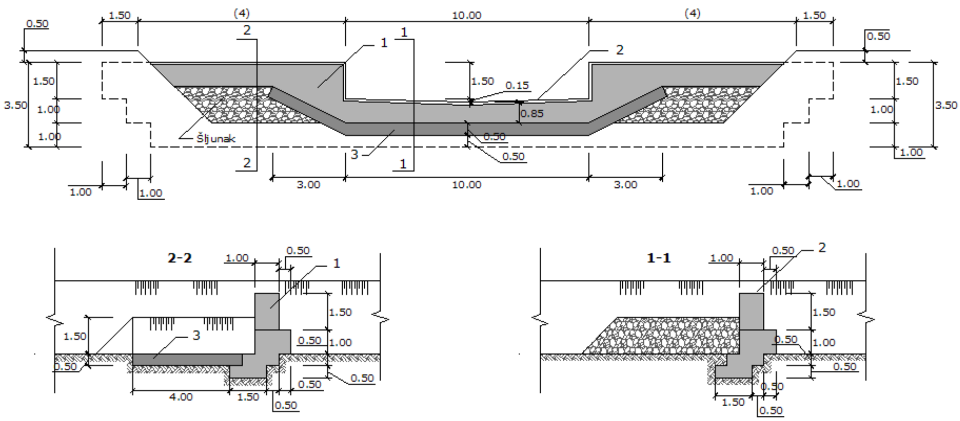

Fig. 5 Typical transverse cross section [5]

In the catchment area of the Ljiljanska river, erosion control works on sanitation erosion processes were carried out. In order to raise the profound river bed, check dams from gabions were constructed with biological regulations between the check dams. The designed flow capacity is $Q_{2\%}$=25,43 m^3/s. At a distance of 115 m, 11 check dams have been constructed (cascade flow). The river flow discharge profile has a trapeze shape: its bottom width is 10m and slope inclination is 1:2. The formation of a trapeze flow profile provides willow wattles for a distance of 15m, as well as one row of willow seedlings at a distance of 1m along the left and right regulation line. The dimensions of the check dams are adjusted so gabion wire boxes are from 0,5 m to 1,5 m. The weir has a rectangular shape on the check dams with a width of 10 m, and height of 1.5 m. The analysis of the constructive solution is presented in Table 1 [5].

Table 1 Analysis of structural design

<table>
<tr><td colspan="5">I Structural properties</td></tr>
<tr><td>Name of the structure</td><td>Scope of work</td><td>Flexible/ rigid structure</td><td>Free draining</td><td>Erosion velocity</td></tr>
<tr><td>River training works on the Ljiljanska river</td><td>Rehabilitation of the river bed and protection of the village, bridge, roads</td><td>Flexible</td><td>Free draining</td><td>Cascades and willow wattles decreased erosion velocity</td></tr>
<tr><td colspan="5">II Operation/ maintains</td></tr>
<tr><td colspan="3">Repairing</td><td colspan="2">Maintains</td></tr>
<tr><td>Difficult</td><td>Medium
Due to turbulent river flow</td><td>Simple</td><td>Difficult</td><td>Medium difficult
Simple, accessible, low cost</td></tr>
<tr><td colspan="5">III Investment costs</td></tr>
<tr><td colspan="5">Duration, life time period</td></tr>
<tr><td colspan="5">6 to 7 years, after that period repairing works are necessary, wattles - many years</td></tr>
<tr><td colspan="5">IV Environmental issues</td></tr>
<tr><td colspan="3">Environmentally friendly</td><td colspan="2">Landscape</td></tr>
<tr><td colspan="3">The solution is environmentally friendly</td><td colspan="2">Due to major floods, the landscape has been destroyed, after construction works, greening is planned</td></tr>
<tr><td colspan="5">V Work performance</td></tr>
<tr><td>Land ownership</td><td colspan="2">Work impact</td><td colspan="2">Local acceptance</td></tr>
<tr><td>To expropriation problems solved</td><td colspan="2">Road damages</td><td colspan="2">Good</td></tr>
<tr><td colspan="5">VI Alternatives for better achievement</td></tr>
<tr><td colspan="5">Alternative rigid solutions with deteriorating impact on the environment and landscape, higher cost, more difficult to maintain and repair, which decrease erosion velocity (concrete structures)</td></tr>
</table>

3. CONCLUSION

Protection of the environment is an imperative of the modern era, and in this respect there must be a general social consensus. All scientific disciplines related to nature, whether directly or indirectly, must take ecology into account. In this framework, water has a very important role to play because of the huge importance of water for the environment. Any approach to the development and use of water courses must be based on the harmonization of water management and environmental objectives. Regardless of the current financial state of the Serbian Water Management, this approach must be our commitment to the future.

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EKOLOŠKI PRIHVATLJIV PRISTUP U HIDROTEHNIČKOJ PRAKSI. STUDIJA SLUČAJA NA LJILJANSKOJ RECI

U proteklih trideset godina ulažu se značajno veći napori da bi se zaštitila rečna korita i obale reka. Izbor i projektovanje odgovarajućeg konstruktivnog rešenja podrazumeva nalaženje rešenja koje je skladu sa principima gradnje ali i geomorfologijom rečnog toka. Na ovaj način se izbegava mogućnost urušavanja regulisanog rečnog korita i vertikalna i bočna erozija rečnog korita čime bi došlo do loma konstrukcije, značajno ugrožavanje rečnog toka i okolnih poseda. S druge strane, konstrukcija treba da bude ekološki prihvatljiva. Hidrotehničke konstrukcije generalno imaju snažan uticaj na životnu sredinu, tako da nalaženje „pravog rešenja" predstavlja pravi izazov za inženjere.

Ključne reči: *hidrotehničke konstrukcije, uticaj na životnu sredinu, uređenje vodotoka*

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Original scientific paper

THE SCALE AND EFFECT OF PUBLIC INVESTMENTS IN FLOOD CONTROL INFRASTRUCTURE IN SERBIA FROM 2009 TO 2021

UDC 626/627

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Abstract. *Flood control structures play an important role in saving lives and property during floods, especially due to climate change issues. The construction, reconstruction, and rehabilitation of hydraulic structures are compliant with their maintenance and are performed periodically and preventively in order to achieve their required functional safety. However, over the years, investments in flood protection, i.e. the reduction of possible damage caused by the harmful effects of water, mostly implied investments in embankments. Investments in high dams are insufficient in terms of their importance, structure complexity, and failure risk.*

Key words: *water management, investments, hydraulic infrastructure, flood control structures, high dams*

1. INTRODUCTION

Investments are a necessary requirement in the permanent human effort to control natural forces and use them to meet needs as efficiently as possible.

Water is the basis for the development of sociological, economic, and ecological activities of an area [1]. In the near future, according to world experts, countries that invest the most in hydraulic infrastructure will be the leaders of economic development on the global water market. It is believed that this market will replace the oil and gas market [2].

People have had a fear of water and what water can do since ancient times. In the light of climate changes, both issues have gained public attention.

Hydraulic infrastructure is the most critical infrastructure. It provides water with the required quality and quantity to users, and also protects from the harmful effects of water [3].

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Flood control structures play an important role in saving lives and property, especially due to climate change issues.

The construction, reconstruction, and rehabilitation of hydraulic structures are compliant with their maintenance and are performed periodically and preventively in order to achieve the required functional safety.

However, over the years, investments in flood protection, i.e. the reduction of possible damage caused by the harmful effects of water, mostly implied investments in embankments. Investments in high dams are insufficient in terms of their importance, structure complexity, and failure risk. The paper analyzes investments in hydraulic infrastructure in the area of narrow Serbia in the period 2009-2021.

2. Understanding Hydraulic Infrastructure Management

Hydraulic infrastructures fall under the category of civil engineering, along with other structures which are used to perform activities related to water resources management.

Hydraulic structures are classified into several categories: river training structures, flood control structures, erosion control structures, irrigation canals, hydraulic structures for water consumption, wastewater conveying and treatment, water protection, and water monitoring.

Flood control structures are embankments with related structures (locks, pumping stations), bank protection, piers and water retaining channels, dams and reservoirs with related structures, retentions, and others.

The maintenance of hydraulic structures which are public property implies construction, reconstruction, rehabilitation, the regular and investment maintenance of hydraulic structures on public property, land improvement, preserving and taking care of their intended use.

Integrated water management is a set of measures and activities aimed at maintaining and improving the water regime, providing the necessary quantities of water of the required quality for various purposes, the protection of water from pollution, and protection from the harmful effects of water [4].

Dams and reservoirs are hydraulic structures of special importance in the flood defense system.

3. Basic Flood Protection Regulations in Serbia

Water resources management is the responsibility of the Republic of Serbia. The Republic of Serbia manages water resources through the Ministry of Agriculture, Forestry and Water Management (its operational body is the Republic Water Directorate) and other competent ministries, bodies of the autonomous province, bodies of the local government unit, and public water management companies [1].

The basic law that regulates issues related to surface and groundwater is the Law on Waters from 2010.

Directive 2000/60/EC of the European Parliament and of the Council, establishing a framework for Community action in the field of water policy, and Directive 2007/60 / EC of the European Parliament and of the Council, on the assessment and management of floods, are basic regulations at the European Union level in the field of flood protection.

In Serbia, the harmonization of legal regulations in that area with community law is in progress.

The territory of the Republic of Serbia is a single water area, divided into 5 water areas.

All surface waters on the territory of Republic of Serbia are classified into waters of the first and waters of the second order.

The public water management company manages hydraulic structures for river regulation and flood protection on waters of the first order.

Hydraulic structures for river regulation and flood protection on waters of the second order and other water structures for erosion and torrent control that are public property are managed by local government on whose territory the structures are built.

4. Investment in Flood Control Infrastructure in Serbia, 2009-2021

In Serbia, river training structures and flood protection structures which are public property are considered structures for protection against the harmful effects of external waters (external flood protection): embankments and regulated riverbeds: 3.700 km, an irrigation network of 25.800km, 200 pumping stations, and 59 dams with reservoirs with space to retain flood waves.

These structures protect towns, settlements, industrial areas, infrastructure, and agricultural land.

The most important precondition for the successful implementation of a flood defense for the protection of defended areas is to ensure the functioning of regulatory and protection structures, which is achieved through preventive work on regular and investment maintenance of regulated rivers and structures in riverbeds, embankments, dams, and reservoirs.

The maintenance of hydraulic structures for erosion protection and torrents and the maintenance of riverbeds outside the defended areas also have a preventive character.

From 2009 till 2021, investments in structures for protection against the harmful effects of water have changed (Fig.1).

After the catastrophic flood events in 2014 and 2016, and later in 2017, 2018, 2019 and 2020, within the state reconstruction programs, numerous emergency rehabilitation works were successfully completed at over 550 critical sites, which contributed to the improvement of the stability and reliability of flood protective structures regarding the state before the mentioned flood events [5].

If we compare the investments from 2010 and 2011, i.e. 2014 and 2015, we can see a jump initiated by damage due to catastrophic floods. Significantly small investments were noted in 2009 and 2013. This indicates an investment trend related to flood damage reduction. The problem is that investment should not follow natural catastrophes, it should prevent them. Prevention is the primary measure for protection against floods and torrents and all these measures have been conducted within passive flood control.

In the last three years, public investment has increased four times compared to the ten-year period (Fig. 1).

Investments in water structures for flood protection have yielded results and the occurrence of floods has been significantly reduced in recent years.

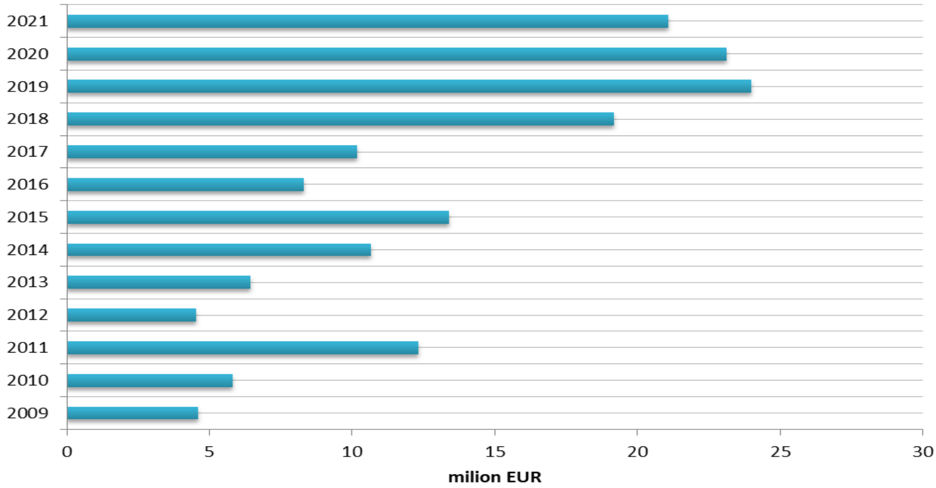

Fig. 1 Total investments in flood protection structures in Serbia, 2009-2021

However, passive measures do not affect the water regime, i.e. they cannot reduce the peak of the flood wave. Reduction of the peak of the flood wave is achieved by active measures, by constructing multi-purpose dams and reservoirs, small dams and retentions. In this context, active flood protection measures should be promoted as much as possible.

If we look at the fund distribution, we can see that most of the funding is oriented toward passive measures. Investments in the maintenance of the existing flood control infrastructure is about 50% of the total investment funds (from 40 to 62%), of which only 7 to 0.9% were allocated for investment maintenance of dams and reservoirs, structures of the highest risk (Table 1 and Table 2).

Table 1 Type of investments, 2009-2015 (million EUR)

Structure type / Year	2009	2010	2011	2012	2013	2014	2015
FCS regular maintenance maintenance	2,33	2,76	2,20	2,20	4,02	4,64	4,88
High dam maintenance	**0,33**	**0,43**	**2,91**	**0,25**	**0,43**	**0,52**	**0,54**
Irrigation system maintenance	0,00	0,00	3,23	0,91	0,96	1,84	2,08
Construction and reconstruction of FCS	1,38	1,53	1,88	0,69	0,67	1,00	0,50
Rehabilitation of FCS	0,33	0,36	0,83	0,23	0,58	1,08	3,29
Implementing FC measures	0,08	0,50	1,13	0,18	0,06	0,20	0,88
Erosion control	0,14	0,24	0,13	0,06	0,09	0,13	0,38

Table 2 Type of investments, 2016-2021 (million EUR)

Structure type / Year	2016	2017	2018	2019	2020	2021
FCS regular maintenance maintenance	4,00	5,23	8,75	10,92	11,25	10,64
High dam maintenance	**0,25**	**0,09**	**0,31**	**0,43**	**0,83**	**0,67**
Irrigation system maintenance	1,28	2,44	4,17	4,54	4,50	3,58
Construction and reconstruction of FCS	0,28	0,39	0,97	1,92	1,21	1,03
Rehabilitation of FCS	0,46	0,12	1,59	1,25	1,22	1,26
Implementing FC measures	0,42	0,08	0,42	0,92	0,83	0,01
Erosion control	0,14	0,04	0,06	0,11	0,11	0,11

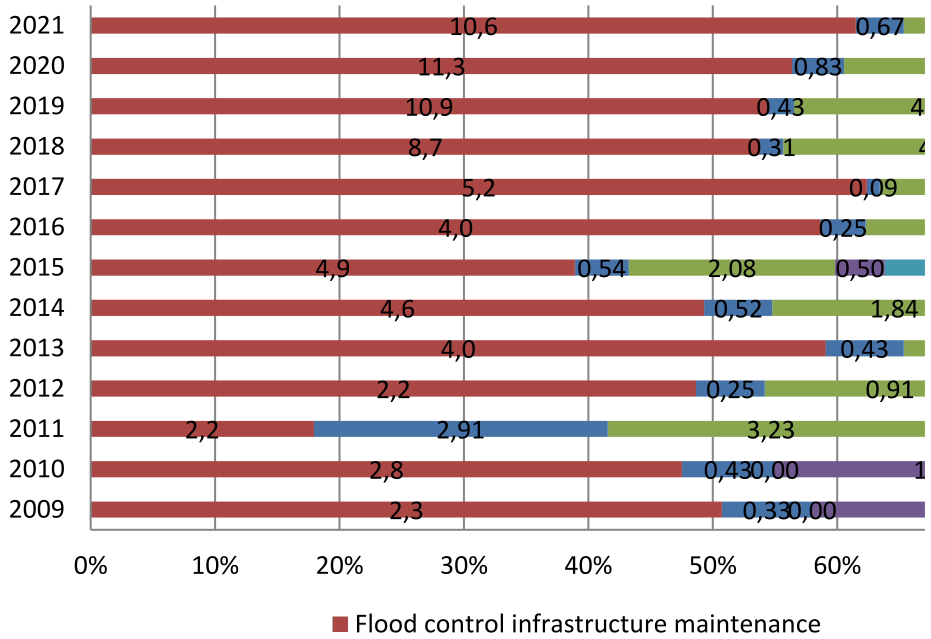

Fig. 2 Percentage by type of investment, 2009-2021

The exception is the year 2011, when an additional 1 million euros were allocated by urgent procedure for the revitalization of a dam after the catastrophic floods in 2010. This percentage has been hovering at 3% in recent years (Fig 2).

Insufficient funds have been allocated for the performance of protective biological and biotechnical erosion control works as well. In recent years, the percentage of allocated funds is less than 1%. The problem of changing the runoff coefficient due to erosion is especially noticeable in West Serbia, where we have continual flooding.

In Table 1 and Table 2 we can see that special importance is given to investing in the maintenance and construction of new irrigation systems.

It is important to point out that the only stable sources of water for irrigation are multi-purpose reservoirs created by high dams. During the design process, part of the useful volume of the reservoir is intended for irrigation.

As the reservoirs were built more than 50 years ago, a revision of water quality and quantity in the reservoir is necessary.

The risk of failure of old dams increases due to changes in the hydrological regime. In that context, modified dam release operations should be performed in order to obtain historical flood protection levels [6].

With the current funds, appropriate maintenance and revitalization of dams and reservoirs are not possible.

5. CONCLUSIONS

All decisions about future investments in flood control structures should be carefully analyzed due to the climate change impact on flood risk [7].

In recent years, in the field of flood protection in the countries of the European Union, the emphasis has been placed on preventive action and flood risk management. In accordance with the Floods Directive, this problem needs to be approached in a different way in Serbia, and some adjustments should be made that will lead to a reduced risk of floods and possible harmful consequences.

The risk of new damage in already flooded areas is significant primarily due to insufficient construction of protection systems, an insufficient level of protection, non-compliance with other infrastructure facilities, and unplanned use of the river bank in protected areas.

The capital projects for the reconstruction of protection systems in the most endangered areas of Serbia are of special importance for investments.

Planned structural measures - works, for which significant funds have already been allocated from foreign sources of financing, are based on the application of integrated conceptual solutions for protection.

Regular and investment maintenance of dams and reservoirs which function in flood defense is of special importance for their functional readiness.

Nevertheless, investments in regular and investment maintenance of high dams are insufficient compared to investments in other parts of the flood protection system.

Due to the long-term lack of financial resources, maintenance on a number of high dams has been reduced to a minimum, which has decreased the functional safety of these capital facilities. Therefore, there is a visible risk of accidents that could endanger human lives and property in the downstream area.

High dams are structures of the highest risk, constructed more than 50 years ago. It is necessary to invest in the revitalization of these structures in order to achieve their full functionality and to extend their service life.

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PROCENA I UTICAJ JAVNIH INVESTICIJA U VODNE OBJEKTE ZA ZAŠTITU OD POPLAVA U SRBIJI U PERIODU 2009-2021

Vodni objekti za zaštitu od štetnog dejstva voda imaju važnu ulogu u spašavanju života ljudi i imovine. Ulaganja u ove objekte mogu biti investiciona u smislu izgradnje, rekonstrukcije, sanacije i održavanja hidrotehničkih objekata, koja se usklađuju sa redovnim održavanjem i izvode se periodično i preventivno u cilju postizanja njihove potrebne funkcionalne sigurnosti. Međutim, godinama unazad su ulaganja u hidrotehničku infrastrukturu uglavnom podrazumevala dominantna ulaganja u nasipe i obaloutvrde. Ulaganja u visoke brane nisu dovoljna s obzirom na njihov značaj, složenost konstrukcije i rizik usled rušenja.

Ključne reči: *upravljanje vodama, investicije, hidrotehničke konstrukcije, vodni objekti za odbranu od poplava, visoke brane*

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